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PWS-0195-0001

Determination of Land Subsidence Related to Ground-Water-Level Declines Using Global Positioning System and Leveling Surveys in Antelope Valley, Los Angeles and Kern Counties, California, 1992

By MARTI E. IKEHARA *and* STEVEN P. PHILLIPS

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS REPORT 94-4184

Prepared in cooperation with the
Antelope Valley Water Group

Sacramento, California
1994

U.S. DEPARTMENT OF THE INTERIOR
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PWS-0195-0003

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS, ACRONYMS, AND WELL-NUMBERING SYSTEM

Conversion Factors

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
foot (ft)	0.304785	meter
foot per year (ft/yr)	0.304785	meter per year
inch (in.)	2.54	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer

Coordinates determined by Global Positioning System (GPS) surveying are generally reported in metric units. The industry standard for GPS usage is that field measurements and subsequent computations, including standard error determinations, are done in the metric system. However, historical land-surface elevations were measured in feet during leveling surveys. Because most of these data were measured in the inch-pound system, GPS-derived elevations were converted from the metric system so that comparisons could be made with historical elevations. The use of dual units in this report is intended to facilitate application of the data by maintaining the integrity of the original units of measurement for GPS and leveling surveying.

Vertical Datum

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD29)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929. "Mean sea level" is not used with reference to any particular vertical datum; where used, the phrase means the average surface of the ocean as determined by calibration of measurements at tidal stations.

Abbreviations

m, meter
mm, millimeter
MHz, megahertz
ppm, parts per million
km, kilometer

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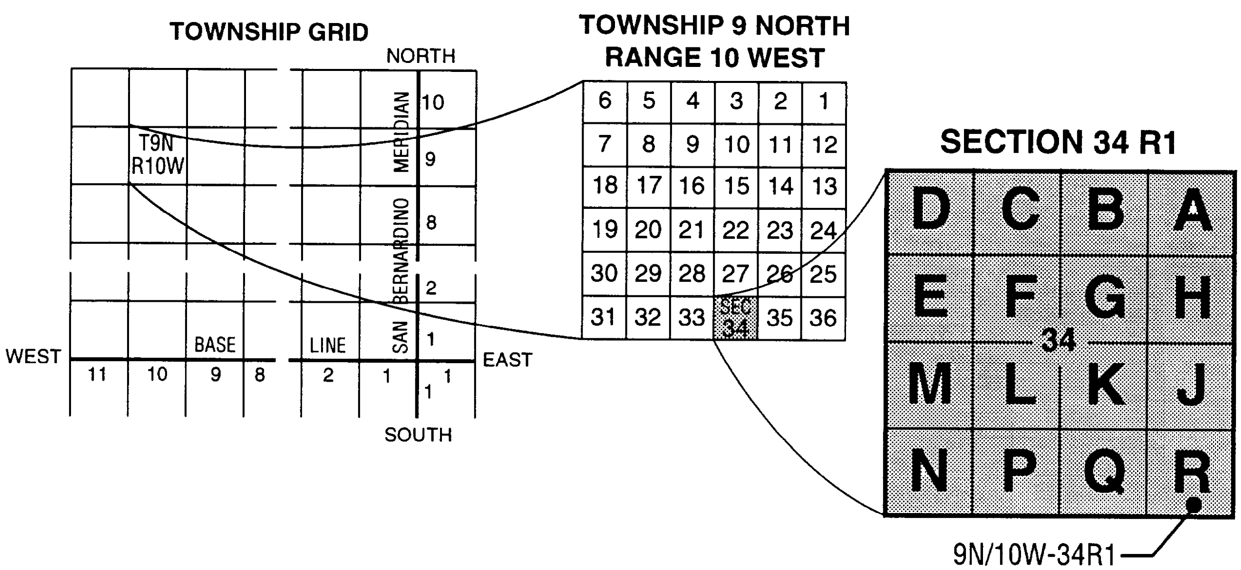
Acronyms

AVEK, Antelope Valley-East Kern
AVWG, Antelope Valley Water Group
BM, Bench Mark
DPW, Department of Public Works
EAFB, Edwards Air Force Base
GPS, Global Positioning System
H.I., Height of Instrument
HPGN, High Precision Geodetic Network
LAC, Los Angeles County
NCMN, National Crustal Motion Network
NGS, National Geodetic Survey
NMD, National Mapping Division
RMSE, Root Mean Square Error
SA, Selective Availability
SCRP, Southern California Releveling Program
SEUW, Standard Error of Unit Weight
USC&GS, U.S. Coast and Geodetic Survey
USGS, U.S. Geological Survey

Well-Numbering System

Wells are identified and numbered by the State of California according to their location in the system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a boustrophedonic manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians: Humboldt (H), Mount Diablo (M), and San Bernardino (S). Because all wells in the study area are referenced to the San Bernardino base line and meridian (S), the final letter will be omitted. Well numbers consist of 15 characters and follow the format 009N010W34R1. In this report, well numbers are abbreviated and written 9N/10W-34R01. The following diagram shows how the number for well 9N/10W-34R1 is derived.



PWS-0195-0007

Determination of Land Subsidence Related to Ground-Water-Level Declines Using Global Positioning System and Leveling Surveys in Antelope Valley, Los Angeles and Kern Counties, California, 1992

By Marti E. Ikehara *and* Steven P. Phillips

Abstract

Land subsidence has occurred where compressible sediments are present in Antelope Valley, California, as a result of ground-water-level declines, particularly in the Lancaster ground-water subbasin. A large-scale monitoring network of bench marks was established in Antelope Valley for the purposes of calculating historical subsidence and enabling precise measurements for future subsidence calculations. Geodetic surveying of 85 stations was done using Global Positioning System (GPS) during 35 days of observations in 1992. The results of this survey indicate that the 95-percent confidence (2σ) level of accuracy for the elevations of these 85 stations generally ranged from ±0.010 meter (0.032 foot) to ±0.024 meter (0.078 foot).

Using results from the 1992 GPS survey and elevations from differential-leveling surveys spanning more than 60 years, the magnitudes and rates of land subsidence from about 1930 to 1992 were calculated for 218 bench marks throughout Antelope Valley. The maximum calculated magnitude of land subsidence was 6.0 feet (1.83 meters) between 1926 and 1992 near Avenue I and Sierra Highway. The maximum estimated magnitude of land subsidence was 6.6 feet (2.01 meters) between about 1930 and 1981 near Avenue I and Division Street. A contour map of land subsidence shows a 210-square-mile (542-square-kilometer) area of Antelope Valley, generally bounded by Avenue K, Avenue A, 90th Street West, and 120th Street East, has subsided between 2 and 7 feet (0.61 and 2.13 meters).

Land subsidence in Antelope Valley is caused by aquifer-system compaction that is related to ground-water-level declines and the presence of fine-grained, compressible sediments. The potentiometric surface of the Lancaster ground-water subbasin of Antelope Valley was mapped for selected years from data collected for the ground-water-monitoring program operated cooperatively by the U.S. Geological Survey and the Antelope Valley-East Kern Water Agency. Comparison of potentiometric-surface, water-level-decline, and subsidence-rate maps for several periods indicated a general correlation between water-level declines and the distribution and rates of subsidence.

Aquifer-system compaction in Antelope Valley has resulted in a reduced volume of void space within the compressed sediments that comprise the solid matrix of the aquifer system. Consequently, the porosity of the compressed sediments and the ground-water storage capacity of the aquifer system also have been reduced. A conservative estimate of the amount of the reduction in storage capacity of the aquifer system in the Lancaster ground-water subbasin is about 50,000 acre-feet in the area [290 square miles (750 square kilometers)] that has been affected by more than 1 foot (0.30 meters) of land subsidence as of 1992.

Information on the history of ground-water levels and the distribution and thickness of fine-grained compressible sediments in Antelope Valley can be used by water managers to mitigate continued land subsidence. Subsidence can be reduced or stopped by maintaining ground-water levels above a region's precon-

solidation head, which is related to the historically lowest ground-water level to have occurred in that region. Future monitoring of ground-water levels in subsidence-sensitive regions of the valley may be an effective means to manage land subsidence.

INTRODUCTION

Land subsidence, related to ground-water-level declines resulting primarily from ground-water withdrawals, historically has been a problem in parts of Antelope Valley, California (fig. 1) (Poland, 1984). Land subsidence is a dynamic process with changes in the causal factors affecting the magnitude, distribution, and rates of subsidence (Poland and others, 1975; Ireland and others, 1984; Ireland, 1985). Ground-water use in the valley was at its highest in the 1950's and 1960's (about 400,000 acre-ft in 1953), primarily as a result of agricultural demand, but sharply decreased to about 82,000 acre-ft between 1968 and 1972 (Templin and others, 1994). The combination of increased pumping lifts because of ground-water-level declines and escalating costs for electric power caused a steady decrease in agricultural production. However, rapid urban development, which began in the 1980's, has resulted in renewed demands for the valley's water resources that lately have been met by increased ground-water pumping. Imported surface water from the State Water Project, first available to Antelope Valley in 1972, was insufficient to meet demands during the 1976-77 drought and from 1990 to 1992, during the 1987-92 drought (Wallace Spinarski, Antelope Valley-East Kern Water Agency, written commun., 1993). Long-term, recurring measurement of areally distributed land-surface elevations is essential for the determination of the cumulative magnitude of subsidence and for the assessment of the geographic extent and changes in rates of subsidence.

Antelope Valley is in the western part of the arid Mojave Desert in southern California, about 50 mi northeast of Los Angeles (fig. 1). The triangular-shaped valley is bounded on the south by the southeast-trending San Gabriel Mountains, on the northwest by the northeast-trending Tehachapi Mountains, and by lower hills, ridges, and buttes in the north and east. The valley is a topographically closed basin with surface-water runoff terminating in several playas.

Ground-water-level declines and the consequent incidence of land subsidence have been attributed to ground-water withdrawals where compressible sediments are present (Poland and others, 1975), and both can be particularly severe where large quantities of ground water have been pumped. Land subsidence has caused sinkholes and fissures near Lancaster and on Edwards Air Force Base (Thomas Holzer and Malcolm Clark, U.S. Geological Survey, written commun., 1981; Blodgett and Williams, 1992; Geolabs, 1991). Other known effects of land subsidence in Antelope Valley include well-casing failures and unstable vertical-control stations. Differential amounts of subsidence, especially across distances of only a few miles, commonly result in damage to engineered structures and utility infrastructures, particularly long linear ones such as pipelines, canals, and aqueducts. Additional potential effects of land subsidence include flooding as a result of altered drainage channel gradients, loss of development potential of vertically unstable real estate, increased insurance costs, and legal implications related to culpability.

In 1992, the sixth year of drought, concerns about current and probable future shortages of surface-water availability and long-term declines in ground-water levels were underscored. Water demands related to projected population growth are expected to increase rapidly in the next decade in Lancaster and Palmdale (Templin and others, 1994). The potential for increased reliance on ground water to satisfy increased water demands may adversely affect aquifer systems in Antelope Valley, particularly Lancaster ground-water subbasin, and may increase the potential for land subsidence. To investigate these concerns, a cooperative agreement between the U.S. Geological Survey (USGS) and the newly formed Antelope Valley Water Group (AVWG) in 1992 authorized a preliminary water-resources management study. Members of AVWG that contributed funds toward this study include the following public and private water-related agencies: Los Angeles County (LAC), Department of Public Works (DPW), Waterworks and Sewer Maintenance Division; Antelope Valley-East Kern Water Agency; City of Palmdale; City of Lancaster; Palmdale Water District; Rosamond Community Services District; and Antelope Valley United Water Purveyors. Some data and results from a cooperative geohydrologic study with Edwards Air Force Base (EAFB), which began in 1989, also were used in this investigation. The goals of the preliminary

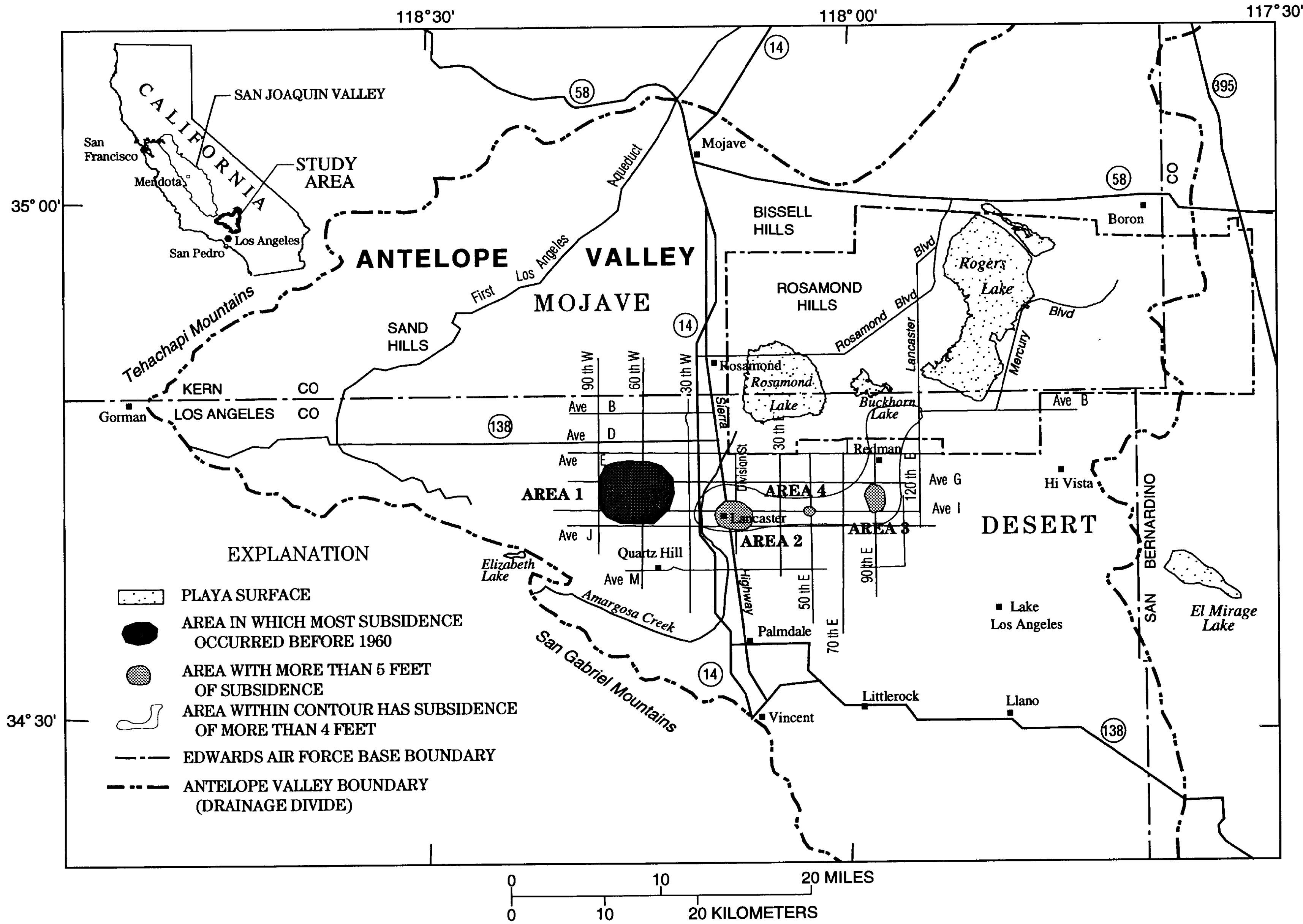


Figure 1. Location of study area and areas of land subsidence, Antelope Valley, California.

water-resources management study were to (1) quantify historical and estimate future water sources, uses, and demands; (2) determine the magnitude and areal extent of land subsidence; and (3) prepare detailed study plans to evaluate the aquifer system and to develop ground-water-flow and optimization models for use as resource allo cation tools in managing the valley's water resources. This report fulfills the second goal of the preliminary Antelope Valley water-resources management study.

Land subsidence has been calculated by comparison of elevations from various differential-leveling surveys of bench-mark networks made during the past 65 or so years. It has become increasingly difficult to make elevation adjustments among the different leveling surveys because of the localized nature of the networks and variable areal rates of land subsidence in Antelope Valley. Global Positioning System (GPS) geodetic surveys of a newly established valleywide network were done in 1992 to establish a vertical-control network for the region based on a single datum, to determine the current magnitude and areal distribution of land subsidence, and to facilitate future monitoring of land subsidence.

Purpose and Scope

The purposes of this report are to (1) characterize the geohydrologic environment of Antelope Valley with respect to the phenomenon of land subsidence; (2) discuss the results, accuracy, and limitations of land-surface elevations that historically have been determined by differential leveling and that were determined by GPS surveys in 1992; (3) quantify the cumulative magnitude, rates, and distribution of land subsidence based on the 1992 GPS survey and historical differential-leveling surveys; and (4) relate the occurrence of land subsidence to observed ground-water-level declines within the geohydrologic framework of Antelope Valley.

The geology, subsurface lithology, tectonic environment, and hydrology of Antelope Valley are briefly characterized in this report, and the mechanics of aquifer-system compaction within this geohydrologic framework are explained. The accuracy and limitations of leveling data, measured by different agencies using different locally adjusted vertical-control datums, are discussed relative to land-subsidence calculations. The use of GPS geodetic surveying in a land-subsidence monitoring application is presented and criteria for selection of network stations are explained. The GPS-surveying methodology used in data collection, postprocessing methodology, and results of network adjustments for 85 stations are documented. Comparisons were made between various historical measurements and the most recent elevation measurements to determine the magnitudes and rates of land subsidence for 218 bench marks in Antelope Valley (table 1). Contour maps are presented to show the magnitude and distribution of subsidence between about 1930-92 and subsidence rates for six variable-length time periods between 1957-92. Hydraulic heads measured in ground-water observation wells in the Lancaster ground-water subbasin were contoured to map potentiometric surfaces for selected years and water-level changes for selected periods. These maps and selected hydrographs illustrate the relation of subsidence to historical ground-water-level declines. The accuracy of measurements from the GPS survey and current calculated rates of subsidence were considered in estimating the appropriate frequency of future subsidence monitoring in Antelope Valley.

Previous Investigations

Several land-subsidence studies of Antelope Valley have been done by the county of Los Angeles. A report prepared by the Office of the County Engineer for Los Angeles County presents elevation differences of selected bench marks in Antelope Valley between 1928 and 1960 (Mankey, 1963). This report includes average annual rates of subsidence for these bench marks, as well as a contour map showing generalized rates of vertical land-surface movement. The maximum magnitude of subsidence for this period was 2.2 ft near Avenue I and 40th Street West, west of Lancaster, in Area 1 on figure 1. The maximum rate of subsidence reported was 0.09 ft/yr, calculated for a 14-year period (1946-60) for three bench marks and for a 19-year period (1941-60) for another bench mark. These four bench marks were along Avenue I between 55th Street West and 70th Street West.

A subsequent report by the Office of the County Engineer for Los Angeles County (McMillan, 1973) presented their earliest and most recent (1972) leveled elevations and the elevation differences for selected bench marks in Antelope Valley between 1935 and 1972. About 1,300 additional bench marks were used to prepare a contour map showing the rate of vertical movement from 1967 to 1972.

Table 1. Map number, alternate name, latitude, longitude, and universal transverse mercator coordinates for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties

[Map numbers refer to bench-mark locations in figures 7 or 8. Latitude and longitude are referenced to NAD83 (with error of 5-10 seconds), determined by digitizing from 1:100,000-scale map unless preceded by footnote. NAD83, North American Datum of 1983; UTM, universal transverse mercator; NCMN, national crustal motion network; SC, section corner; OS, offset; RS, reset; m, meter]

Map No.	Bench-mark name	Alternate names	Latitude	Longitude	UTM *x*-coordinate (m)	UTM *y*-coordinate (m)
1	BM 53		34°42'14"	118°07'51"	396434	3840592
2	BM 56		34°42'15"	118°07'19"	397249	3840615
3	BM 60	Y488 1961	34°42'11"	118°06'43"	398163	3840480
4	BM 73		34°40'29"	118°06'44"	398103	3837340
5	BM 85		34°40'30"	118°08'56"	394744	3837407
6	BM 118	S811 RS1955, 101-127	34°40'54"	118°08'00"	396178	3838130
7	BM 120		34°42'14"	118°09'22"	394119	3840618
8	BM 121		34°42'08"	118°09'27"	393990	3840434
9	BM 135	H306 1935	[1]34°31'16"	117°57'54"	411429	3820165
10	BM 171	E306 1935	[1]34°34'49"	118°02'45"	404077	3826800
11	BM 172	F489 1955	34°38'45"	118°12'07"	389845	3834229
12	BM 185	SC 7N/13W	34°40'27"	118°13'08"	388330	3837390
13	BM 271A	SC 7N/10W	34°41'24"	117°58'02"	411404	3838895
14	BM 278A	SC 7N/10W	34°42'16"	117°58'01"	411445	3840497
15	BM 283	107-30 1961	34°42'13"	118°00'24"	407806	3840440
16	BM 287A		34°43'11"	117°58'05"	411360	3842192
17	BM 316		34°42'15"	118°05'42"	399717	3840588
18	BM 330	D489 1955	34°38'45"	118°09'53"	393256	3834189
19	BM 336	E489 1955	[1]34°38'45"	118°10'55"	391678	3834207
20	BM 397	SC 6N7N/13W	34°38'40"	118°14'10"	386711	3834113
21	BM 417	SC 7N/11W	34°44'01"	118°01'26"	406263	3843783
22	BM 426	SC 8N/11W	34°44'55"	118°00'23"	407882	3845430
23	BM 471	B57 RS1955, 101-124	[1]34°39'24"	118°07'47"	396477	3835354
24	BM 472	T811 1947, 101-125	34°40'03"	118°07'51"	396389	3836556
25	BM 474	B2335 1902, 101-133	[1]34°42'26"	118°08'16"	395803	3840968
26	BM 476	Z811 1947, 101-136	34°43'54"	118°08'38"	395274	3843685
27	BM 477	Y56 1926, 101-138	34°44'35"	118°08'36"	395339	3844948
28	BM 479	OBAN 1929 LINT, 101-141	[2]34°45'15"	118°08'47"	395073	3846183
29	BM 481	H487 1955	34°45'43"	118°08'48"	395058	3847046
30	BM 482	J487 1955, 101-147	34°47'29"	118°09'06"	394638	3850317

Footnotes at end of table.

PWS-0195-0012

Table 1. Map number, alternate name, latitude, longitude, and universal transverse mercator coordinates for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Bench-mark name	Alternate names	Latitude	Longitude	UTM *x*-coordinate (m)	UTM *y*-coordinate (m)
31	BM 483	N487 1955	34°48'23"	118°09'09"	394580	3851981
32	BM 484	M487 1955, 101-151	34°49'07"	118°09'21"	394291	3853340
33	BM 499		34°45'40"	118°07'56"	396379	3846939
34	BM 537	102-9 1957	[1]34°42'16"	118°12'37"	389159	3840738
35	BM 540		34°42'12"	118°10'59"	391651	3840585
36	BM 545		34°41'25"	117°57'00"	412982	3838911
37	BM 560	SC 7N/11W	34°44'00"	118°04'39"	401354	3843803
38	BM 571		34°45'40"	118°06'19"	398845	3846911
39	BM 577		34°45'41"	118°04'38"	401413	3846914
40	BM 585		34°45'44"	118°02'31"	404643	3846972
41	BM 666		34°42'13"	118°08'14"	395849	3840567
42	BM 714		34°42'07"	118°13'11"	388291	3840471
43	BM 721		34°40'25"	118°10'31"	392325	3837280
44	BM 725	7N/12W	34°40'26"	118°11'33"	390747	3837330
45	BM 820	102-15 1957	34°42'11"	118°15'18"	385061	3840634
46	BM 823	B306 1935, 102-16, US 3170	[1]34°42'15"	118°15'47"	384325	3840766
47	BM 828		34°42'07"	118°17'19"	381981	3840550
48	BM 835		34°43'31"	118°17'26"	381836	3843140
49	BM 839	SC 8N/13W	34°44'46"	118°17'23"	381942	3845449
50	BM 852	8N/13W	34°47'50"	118°17'25"	381964	3851118
51	BM 866	SC 8N/13W	34°48'16"	118°14'15"	386802	3851858
52	BM 878	SC 8N/13W	34°45'39"	118°14'14"	386768	3847021
53	BM 887	SC 8N/13W	34°43'54"	118°14'14"	386728	3843787
54	BM 900	SC 8N/13W	34°46'31"	118°16'21"	383560	3848663
55	BM 966	L306 1935 106-48, US 3378	34°29'54"	117°43'55"	432802	3817460
56	BM 998	LS33 1929, 106-80, US 1982	34°36'59"	117°46'22"	429153	3830578
57	BM 1069	LS17 1929, 106-93, US 1944	34°39'58"	117°49'34"	424308	3836131
58	BM 1078	SC 7N/10W	34°41'22"	117°55'53"	414686	3838803
59	BM 1082		34°41'23"	117°54'53"	416213	3838819
60	BM 1087	SC 7N/10W	34°41'23"	117°53'45"	417943	3838804
61	BM 1090	SC 7N/9W10W	34°41'22"	117°52'42"	419546	3838759
62	BM 1103		34°38'41"	117°51'36"	421183	3833785
63	BM 1146	SC 7N/9W10W	34°43'07"	117°52'41"	419600	3841993
64	BM 1155	SC 8N/9W10W	34°45'47"	117°52'39"	419694	3846921
65	BM 1159	106-116 1959	[1]34°45'50"	117°55'01"	416084	3847046
66	BM 1165A	106-122 1959	34°45'47"	117°57'57"	411609	3846995
67	BM 1165B (Offset)	106-122 1959 OS89	[1]34°45'50"	117°58'15"	411153	3847092
68	BM 1170A	116-4 1961	34°44'00"	117°58'04"	411400	3843701
69	BM 1171A	116-3 1961	[1]34°43'37"	117°58'10"	411240	3842994
70	BM 1182	107-18 1961	34°38'47"	117°58'01"	411383	3834059

Footnotes at end of table.

PWS-0195-0013

Table 1. Map number, alternate name, latitude, longitude, and universal transverse mercator coordinates for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Bench-mark name	Alternate names	Latitude	Longitude	UTM *x*-coordinate (m)	UTM *y*-coordinate (m)
71	BM 1238		34°46'27"	118°25'49"	369119	3848736
72	BM 1254		34°46'26"	118°30'03"	362651	3848091
73	BM 1276	102-52 1957	[1]34°45'40"	118°30'49"	361471	3847398
74	BM 1290	102-38 1957	[1]34°43'49"	118°24'49"	370576	3843846
75	BM 1291		34°43'25"	118°24'43"	370718	3843106
76	BM 1295		34°43'30"	118°22'38"	373900	3843216
77	BM 1302	7N/14W	34°42'08"	118°20'04"	377784	3840635
78	BM 1306	SC 7N/13W14W	34°42'08"	118°18'23"	380353	3840601
79	BM 1327	PC21	34°39'31"	118°22'34"	373901	3835850
80	BM 1380	110-10 1958	[1]34°37'01"	118°09'23"	393983	3830976
81	BM 1456	D1154 1961	34°46'35"	118°10'01"	393220	3848669
82	BM 1469	AVENUE 1960	[1]34°46'36"	118°13'12"	388366	3848758
83	BM 1480	102-60 1957	34°46'29"	118°34'11"	356359	3848988
84	BM 1483	102-63 1957	[1]34°46'32"	118°36'20"	353081	3849131
85	BM 1494	102-73 1957	[1]34°46'23"	118°41'11"	345679	3848975
86	BM 1518	G452 1953	34°47'14"	118°49'11"	333505	3850759
87	BM 2016		34°38'45"	118°05'42"	399646	3834117
88	BM 2030	121-11 1961	[1]34°38'46"	118°01'24"	406215	3834079
89	BM 2037	122-1 1961	[1]34°38'45"	117°57'38"	411968	3833992
90	BM 2041	122-4 1961	34°38'43"	117°55'51"	414692	3833904
91	BM 2045	SC 6N7N/10W	34°38'45"	117°53'47"	417849	3833937
92	BM 2061	Z1044 1960	34°38'41"	118°17'21"	381849	3834204
93	BM 2067		34°39'26"	118°20'25"	377183	3835652
94	BM 2076	7N/14W	[1]34°39'34"	118°22'06"	374615	3835933
95	BM 2078	119-35 1961	34°39'32"	118°22'17"	374334	3835875
96	BM 2140	119-46 1961	34°44'14"	118°19'29"	378725	3844505
97	BM 2169	RDBM 95J	[1]34°41'25"	117°57'39"	411990	3838920
98	BM 2174	106-130 1959	[1]34°45'47"	118°02'29"	404694	3847064
99	BM 2180	107-35 1961	[1]34°42'16"	118°03'01"	403813	3840573
100	BM 2181	G1154 1961	34°42'12"	118°02'29"	404626	3840441
101	BM 2186	F1154 1961	[1]34°45'45"	118°06'47"	398135	3847073
102	BM 2230	SC 8N9N/12W	34°49'08"	118°11'07"	391598	3853402
103	BM 2235	117-6 1961	[1]34°49'12"	118°12'10"	389999	3853544
104	BM 2236	8N9N/13W	34°49'08"	118°12'41"	389210	3853431
105	BM 2244	117-10A 1961	34°49'05"	118°14'13"	386872	3853367
106	BM 2290		34°44'51"	118°09'31"	393946	3845457
107	BM 2295	SC 8N/12W	34°44'47"	118°11'04"	391580	3845361
108	BM 2298		34°44'51"	118°11'49"	390437	3845498
109	BM 2300	103-7 1957	34°44'46"	118°12'12"	389850	3845351
110	BM 2301		34°44'48"	118°12'38"	389190	3845420

Footnotes at end of table.

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Table 1. Map number, alternate name, latitude, longitude, and universal transverse mercator coordinates for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Bench-mark name	Alternate names	Latitude	Longitude	UTM *x*-coordinate (m)	UTM *y*-coordinate (m)
111	BM 2317	117-16 1961	[1]34°49'12"	118°17'25"	381997	3853644
112	BM 2318	SC 8N9N/13W	34°49'07"	118°17'26"	381969	3853490
113	BM 2319		34°49'09"	118°17'57"	381182	3853564
114	BM 2326A	SC 8N9N/14W	34°49'06"	118°19'33"	378742	3853501
115	BM 2344	SC 7N/10W	34°43'08"	117°54'49"	416344	3842053
116	BM 2348		34°43'10"	117°55'56"	414641	3842130
117	BM 2356	8N/10W	34°44'26"	117°54'49"	416366	3844456
118	BM 2368	SC 7N/11W	34°40'29"	118°03'32"	402990	3837285
119	BM 2371	120-6 1961	34°40'32"	118°02'25"	404696	3837360
120	BM 2393	SC 7N8N/9W	34°44'03"	117°48'26"	426100	3843664
121	BM 2395	7N8N/9W	34°45'48"	117°47'54"	426939	3846892
122	BM 2396		34°44'00"	117°47'52"	426964	3843564
123	BM 2409	SC 7N/8W9W	34°42'16"	117°46'20"	429279	3840344
124	BM 2442		34°42'13"	117°48'27"	426047	3840277
125	BM 2616	RDBM 47FTEJON	[1]34°33'06"	118°02'33"	404350	3823624
126	BM 2646	LS28 1929	34°37'51"	118°01'26"	406147	3832385
127	BM 2678	H977 1964	34°30'20"	117°54'16"	416971	3818388
128	BM 2685	Z1045 1960	34°30'16"	117°48'58"	425080	3818196
129	BM 2706	115-4 1961	[1]34°36'08"	117°52'17"	420099	3829081
130	BM 2716	109-4 1961	[1]34°34'48"	117°56'01"	414370	3826668
131	BM 2746	109-19 1961	[1]34°33'01"	117°50'08"	423337	3823293
132	BM 2760		34°38'47"	118°00'21"	407819	3834094
133	BM 3198	SC 6N7N/11W	34°38'44"	118°03'31"	402981	3834051
134	BM 3225	7N/11W	34°40'30"	118°05'08"	400547	3837344
135	BM 3294	7N8N/12W	34°43'59"	118°06'16"	398887	3843799
136	BM 3317		34°47'22"	118°11'04"	391636	3850136
137	BM 3387	SC 8N9N/15W	34°49'01"	118°27'57"	365935	3853525
138	BM 3392	117-32 1961	34°48'59"	118°25'49"	369186	3853417
139	BM 3398		34°38'43"	117°44'44"	431672	3833763
140	BM 3454	8N/8W9W	34°45'22"	117°46'18"	429373	3846072
141	BM 3455		34°45'20"	117°46'20"	429322	3846010
142	BM 3549	117-29 1961	[1]34°49'08"	118°24'21"	371426	3853663
143	BM 3636	119-41 1961	[1]34°46'33"	118°19'32"	378705	3848788
144	BM 3646	106-126 1959	34°45'46"	118°00'20"	407974	3847000
145	BM 3724		34°43'35"	118°00'23"	407857	3842966
146	BM 3738	RDBM 50G8	[1]34°43'36"	118°02'27"	404703	3843029
147	BM 3998	SC 8N9N/14W	34°49'07"	118°22'42"	373941	3853599
148	BM 4116	X973 RS1965	[1]34°46'29"	118°46'09"	338107	3849290
149	BM 4217	W811 RS1973	[1]34°37'34"	118°07'30"	396872	3831960
150	BM 4218		34°38'45"	118°07'38"	396693	3834151

Footnotes at end of table.

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Table 1. Map number, alternate name, latitude, longitude, and universal transverse mercator coordinates for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Bench-mark name	Alternate names	Latitude	Longitude	UTM *x*-coordinate (m)	UTM *y*-coordinate (m)
151	BM 4219	S12-19 1971, 101-122A	34°38'45"	118°07'35"	396769	3834151
152	BM 4360		34°49'04"	118°52'50"	328002	3854251
153	BM 4415		34°42'16"	118°04'36"	401396	3840599
154	BM 4465		34°38'47"	118°02'26"	404637	3834126
155	BM 5159	B2657 1902, US 829	[1]34°34'44"	118°07'01"	397553	3826716
156	BM 5190	GRINELL RS1929	[2]34°45'60"	117°49'10"	425010	3847277
157	BM 5197	B2356 RS1961	34°41'52"	118°08'12"	395893	3839922
158	BM 5199	Z56 RS1965, 101-134A	34°42'49"	118°08'18"	395785	3841679
159	BM 5204	N487 1955 OS89	[1]34°48'19"	118°09'15"	394427	3851859
160	BM 5205	M899 1955, US 4765	[1]34°30'58"	118°06'19"	398547	3819742
161	ALDER 1947		[2]34°51'49"	118°06'42"	398386	3858285
162	Aqueduct 100		[1]34°51'24"	118°29'31"	363612	3857966
163	ARP 1971 PMD	Airport Ref Pt	[1]34°37'46"	118°05'04"	400594	3832289
164	Ask P7		[1]34°52'23"	117°54'46"	416576	3859148
165	B2322 1906		[3]34°55'09"	117°54'38"	416826	3864260
166	BUCKHORN 3 1967		[1]34°50'19"	117°59'43"	408998	3855400
167	BULL		[1]34°49'06"	118°33'12"	357934	3853800
168	D1155 1961		[1]34°53'06"	117°57'57"	411739	3860518
169	F54 1926		34°50'44"	118°52'08"	329126	3857312
170	F1147 1961	101-159	[1]34°52'50"	118°10'03"	393304	3860222
171	GWM2 1937		[1]34°53'45"	117°55'00"	416244	3861678
172	GWM4 1937		[1]34°51'59"	117°57'11"	412888	3858443
173	GWM10 RS1971		[3]35°00'42"	117°52'53"	419580	3874494
174	GWM11 RS1971		35°00'30"	117°50'17"	423531	3874090
175	GWM11 RS1971 OS89		[3]35°00'22"	117°50'14"	423605	3873843
176	H1155 1961		34°50'43"	117°54'57"	416269	3856070
177	H1155 1961 OS89		[1]34°50'42"	117°54'60"	416192	3856040
178	HPGN 0618		[2]34°49'31"	118°52'05"	329161	3855061
179	HPGN 0705		[2]34°29'34"	117°45'54"	429762	3816866
180	HPGN 0805		[1]35°00'26"	117°31'45"	451716	3873774
181	HPGN PEARBLOSSOM	NCMN 7254	[2]34°30'44"	117°55'21"	415321	3819143
182	JUNCTION 1958		[2]35°00'43"	117°54'43"	416793	3874550
183	L68 1928		[3]34°57'35"	117°46'57"	428558	3868659
184	LC68 1952		35°02'18"	117°49'30"	424750	3877407
185	LC68 1952 OS89		[1]35°02'20"	117°49'09"	425282	3877465
186	LS38 1929	US 2173	[1]34°47'32"	118°05'44"	399772	3850352
187	LS39 1929	US 2176	34°47'32"	118°02'26"	404804	3850300
188	LS40 1929	US 2002	34°47'35"	117°59'13"	409710	3850343
189	LS42 1929	US 2003 or 2008	34°48'28"	118°08'12"	417907	3851898
190	LS46 1929		[1]34°41'29"	117°48'37"	425782	3838922

Footnotes at end of table.

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Table 1. Map number, alternate name, latitude, longitude, and universal transverse mercator coordinates for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Bench-mark name	Alternate names	Latitude	Longitude	UTM *x*-coordinate (m)	UTM *y*-coordinate (m)
191	LS53 1929		[1]34°43'59"	117°53'29"	418393	3843606
192	M1155 1961		[1]34°48'43"	117°52'41"	419690	3852343
193	MDC4 1973		[1]34°48'30"	117°49'55"	423904	3851907
194	MDC6 1973		[1]34°48'32"	117°46'28"	429164	3851926
195	MDC30 1973		[1]34°52'10"	117°48'32"	426068	3858666
196	MDC33 1973		[1]34°54'30"	117°47'29"	427702	3862966
197	MONDAY RS1929	Adobe Mtn. F-1	[1]34°44'35"	117°42'21"	435389	3844580
198	P1155 1961		[1]34°48'25"	117°54'56"	416255	3851819
199	Rogers Lakebed 1	1RLB 1989	[1]34°56'37"	117°50'49"	422659	3866920
200	Rogers Lakebed 3	3RLB 1989	[1]34°54'06"	117°50'34"	423001	3862265
201	Rogers Lakebed 4	4RLB 1989	[1]34°49'30"	117°51'33"	421430	3853776
202	Rogers Lakebed 5	5RLB 1989	[1]34°59'45"	117°50'44"	422835	3872710
203	Rogers Lakebed 6	6RLB 1989	[1]34°56'50"	117°47'11"	428192	3867275
204	ROSAMOND	SC 8N9N/11W12W	[1]34°49'17"	118°05'43"	399833	3853586
205	Rosamond Lake 1	1ROL 1989	[1]34°49'02"	118°05'26"	400260	3853119
206	RS38 1932		35°00'08"	117°46'25"	429406	3873365
207	RS38 1932 OS89		[1]35°00'08"	117°46'30"	429280	3873366
208	Santa Fe Trail 1		[1]34°55'29"	117°51'52"	421043	3864839
209	Sewage Treatment Pond 1		[1]34°51'23"	117°52'51"	419479	3857274
210	T1139 1961		[1]34°56'22"	117°54'57"	416364	3866513
211	Transect 8		[1]34°50'59"	117°49'42"	424273	3856494
212	U56 1926	101-156	[1]34°51'36"	118°09'45"	393735	3857937
213	U1154 1961		[1]34°51'55"	118°04'37"	401562	3858435
214	V1146 1961		[1]34°51'10"	118°13'13"	388443	3857199
215	V1155 1961		[1]34°48'29"	117°59'16"	409650	3852005
216	Y1139 1961		[1]34°57'44"	117°53'48"	418137	3869023
217	Y1154 1961		[1]34°52'00"	118°00'37"	407657	3858525
218	Z488 1955		[1]34°42'41"	118°05'49"	399547	3841389

[1] Latitude and longitude referenced to NAD83, measured using GPS in 1992.
[2] Latitude and longitude referenced to NAD83, held fixed for 1992 GPS survey.
[3] Latitude and longitude referenced to NAD83, measured using GPS in 1989.

McMillan also described the limitations of evaluating changes in elevation for long periods of time because of differing datums and adjustment standards that were in effect at the time of elevation determinations. The area with the maximum magnitude and rate of land subsidence between 1967 and 1972 was near Avenue J and 70th Street East, about 14 mi east of the area with maximum subsidence between 1928 and 1960. A rate of subsidence of about 0.3 ft/yr for 1967 to 1972 at this location corresponds to a magnitude of 1.6 ft and represented a threefold increase above the rate of 0.1 ft/yr for the previous period, 1960-67 (McMillan, 1973).

Second- and third-order leveling networks of the Los Angeles County, Department of Public Works, Road Department, supplemented the network of the Los Angeles County Engineer. The leveling surveys of the Road Department, done at recurrence intervals of about a decade or less, also documented land subsidence in and around Lancaster (County of Los Angeles, 1981a, 1991). The area having the maximum calculated magnitude of subsidence, 4.9 ft, for the period 1957-81 was near Avenue I and 90th Street East (Area 3, fig. 1), slightly northeast of the area identified as having the maximum subsidence rate between 1967 and 1972. Nearly 5 ft of subsidence was identified for the same period in Lancaster at Avenue I and Division Street (Area 2, fig. 1).

In the northeastern part of Antelope Valley, bench-mark elevations on and in the vicinity of EAFB were measured between 1989 and 1991 using differential leveling or GPS surveying or both (Blodgett and Williams, 1992). In 1989, a network of 41 bench marks was measured using GPS surveying; about 25 additional bench marks were leveled between 1989 and 1991. The maximum magnitude of subsidence between 1961 and 1989 on EAFB was 3.3 ft near the intersection of Lancaster

Boulevard and Avenue B, southwest of Rogers Lake. In a related study of the hydrogeology of EAFB, sediment compaction was measured using an extensometer constructed near this area of maximum subsidence (Londquist and others, 1993). At this same site, ground-water levels were measured in four piezometers completed at different depths. Data collected between May 1990 and November 1991 showed a higher rate of compaction during the pumping season (about April to September) which corresponded to the water-level declines. The aquifer system continued to compact, albeit at a lower rate, during the autumn and winter, even though water levels recovered.

Acknowledgments

The Los Angeles County, Department of Public Works cooperated with the USGS in collecting GPS and leveling data and by providing their historical leveling data. Joseph Aja of the Waterworks and Sewer Maintenance Division and Robert Reader, Gerald Campbell, Charles Peer, and others of the Survey Division were instrumental in the collection of new data and the sharing of historical surveying data.

Don D'Onofrio, National Geodetic Survey (NGS), National Ocean Service, National Oceanic and Atmospheric Administration, provided invaluable advice on the execution of a large-scale GPS survey, distributed information on the California High Precision Geodetic Network (HPGN) and updates on the geoid separation model prepared by NGS, and participated in data collection for 10 days.

Karl Gross, Office of Earthquakes, Volcanoes, and Engineering, Geologic Division, USGS, loaned three GPS receivers for a total of several weeks during the observation period, assisted in the temporary (field) archival of collected data, and provided advice on several aspects of executing GPS surveys ranging from data-collection intervals to form design for documenting field and office processes.

Michael Duffy, representing Metropolitan Water District of Southern California, loaned two GPS receivers for 2 weeks and provided information about the techniques used in their field and office operations.

Dr. Kenneth Hudnut, California Institute of Technology, provided 3 days of observations for a station being observed as part of a separate GPS survey, the Inter-County Cooperative program.

Jay Satalich, Caltrans District 5, authorized Larry Scott of Johnson-Frank & Associates, Inc. to provide leveling information for HPGN 0618.

The following USGS employees participated in the GPS surveying data collection: Lawrence A. Freeman, Devin L. Galloway, Scott N. Hamlin, Clark J. Londquist, Bernard J. McNamara, Kelly R. McPherson, Diane L. Rewis, and David K. Yancey. The nature and scope of their duties were outside the realm of their usual assignment, and their performance was exceptional—of 167 receiver-days of data collected, only 1 receiver-day of data was unusable.

GEOHYDROLOGIC FRAMEWORK OF ANTELOPE VALLEY

Generalized Physical Geology, Subsurface Lithology, and Tectonics

Underlying Antelope Valley are three large, sediment-filled structural basins, which are separated by areas of extensively faulted, elevated bedrock (Dibblee, 1967; Londquist and others, 1993). These depositional basins, West Antelope Basin, East Antelope Basin, and Kramer Basin (fig. 2), are filled with alluvium and sedimentary and volcanic rocks of Tertiary age. The predominant bedrock types are pre-Tertiary igneous quartz monzonite and granitoid batholiths, with isolated remnants of intensely deformed metamorphic rocks (Dibblee, 1967). Dibblee postulated that the large areas of basement complex that separate the basins probably were highlands that became further elevated as the basins were depressed. Evidence to substantiate this interpretation relates to the difference in sedimentary sequences in each basin and to the coarsening of some formations at basin margins.

The subsurface lithology of unconsolidated sedimentary deposits influences the location and degree of land subsidence that results from aquifer-system compaction of fine-grained sediments. In Antelope Valley, unconsolidated sedimentary deposits of Quaternary age overlie consolidated rocks and are of either alluvial or lacustrine origin. The alluvial deposits consist of unconsolidated to moderately indurated, poorly sorted gravel, sand, silt, and clay (Dutcher and Worts, 1963). The lacustrine deposits are primarily thick layers of blue-green silty clay and a brown clay with interbedded sand and silty sand layers. These deposits accumulated in a lake or marsh that covered large parts of Antelope Valley at the end of the Pleistocene Epoch (Dibblee, 1967). Older alluvium is

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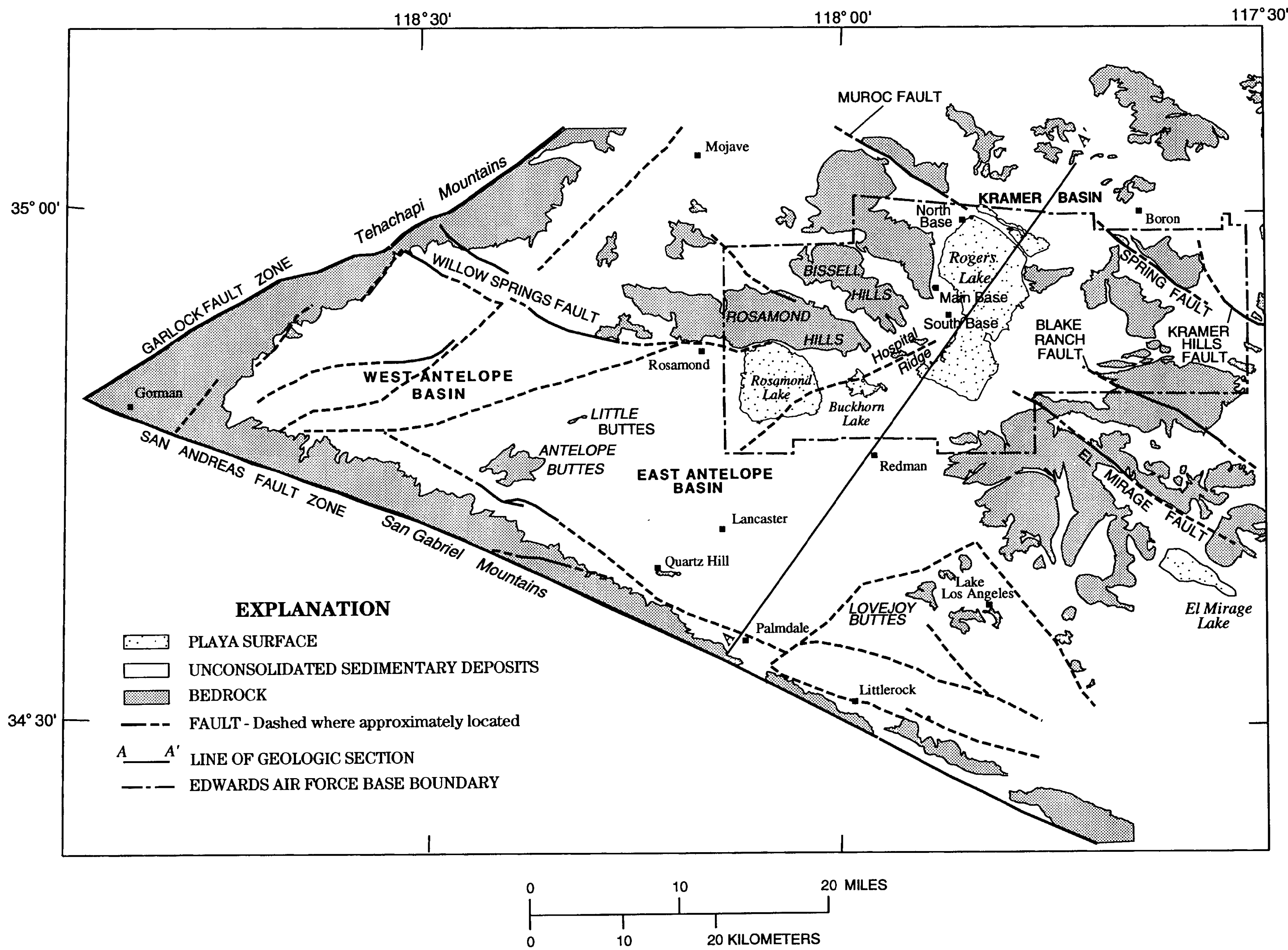

Figure 2. Generalized surficial geology and major faults in Antelope Valley. (Modified from Londquist and others, 1993, fig. 2).

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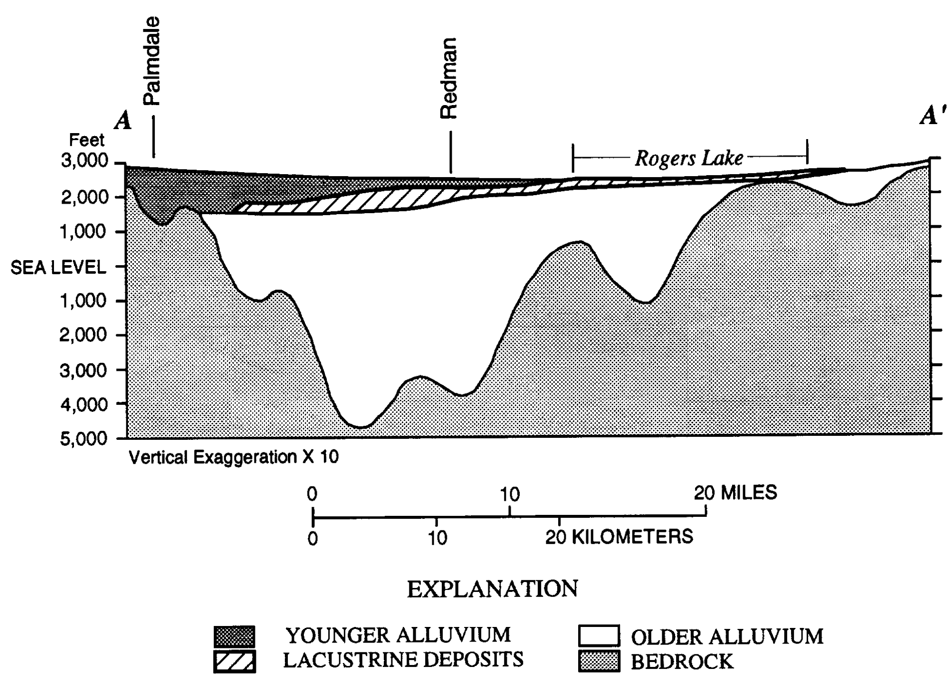

Figure 3. Generalized geologic section showing relation of lacustrine and alluvial deposits. Line of section shown on figure 2. (Modified from Londquist and others, 1993, fig. 3).

overlapped by lacustrine deposits, which are themselves overlapped from the south by younger alluvium (fig. 3). Individual clay beds, locally as much as 100 ft thick, are interbedded with pockets of coarser material as much as 20 ft thick (Londquist and others, 1993).

Crustal extension during the Oligocene Epoch (about 32 million years ago) resulted in the structural basins in the Mojave Desert. A second period of tectonic deformation superimposed predominantly northwest-trending right-lateral faulting over the northeast-trending faults of the Basin and Range topography. The tectonic environment of Antelope Valley is dominated by the San Andreas Fault, which forms the southern boundary of the valley (fig. 2). The San Andreas Fault is a right-lateral, northwest-trending active fault at the northern base of the San Gabriel Mountains. There are several other fault zones and fault traces in the western Mojave Desert, most notably the active Garlock Fault. It is a left-lateral, northeast-trending fault zone at the boundary between the valley and the Tehachapi Mountains (fig. 2). The western end of the Garlock Fault zone terminates at its intersection with the San Andreas Fault zone near Gorman.

In addition, there are several minor faults in Antelope Valley, but they are not considered active (Londquist and others, 1993) and are located outside the extent of most bench marks in the leveling networks. The location of the major active faults at the boundaries of the valley allows points within the valley to be considered tectonically stable relative to each other. Ideally, primary and secondary control stations within a geodetic network would be located in one structural unit.

Research, using hundreds of kilometers of geodetic leveling, indicates that much of Southern California was subject to two periods of tectonic uplift during the 20th century (Mark and others, 1981; Castle and others, 1984; Castle and others, 1987). Antelope Valley, which is in the western half of the Mojave Desert province, is included entirely within the uplifted area. The two periods of tectonic uplift, measured relative to a tidal bench mark at San Pedro on the coast just south of Los Angeles (fig. 1), are 1905-33 and 1959-76. Tectonic activity in Antelope Valley during the early 20th century was characterized by an uplift ranging from 1.15 to 1.31 ft (0.35 to 0.40 m) between 1906 and 1907, relative to a time baseline of 1902, followed by a slight collapse of about 0.33 ft (0.1 m) between 1924 and 1928 (Castle and others, 1987). Elevations for all bench marks used in the current study (1992) were determined after 1925, except bench mark Aqueduct 100 (no. 162, table 1), which was leveled in 1907 and later adjusted to National Geodetic Vertical Datum of 1929 (NGVD29). Thus, the early tectonic episode has had no effect on the determination of land subsidence since about 1930.

The more recent period of tectonic uplift (between 1959 and 1976) had a similar magnitude, history, and areal distribution as the 1905-33 period. Using a time baseline of 1955, land-surface elevation changes in Antelope Valley attributed to tectonic causes in the mid-20th century include the following phases: The inception, with uplift of 0.16 ft (0.05 m) by mid-1961 along the San Andreas Fault zone; uplift of 0.49 ft (0.15 m) throughout the valley with a narrow zone of 0.66-ft (0.20-m) of uplift between Palmdale to the valley boundary east of Llano by 1962; valleywide uplift of 0.66 ft (0.20 m) by 1966; an increase in uplift to 0.98 ft (0.30 m) in a small linear zone between Gorman and Palmdale by mid-1971; a maximum valleywide uplift of 0.98 ft (0.30 m) by 1973, with a small zone of 1.15 ft (0.35 m), again between Palmdale and Llano; followed by a collapse by 1977 with increases in elevation relative to 1955 ranging from only 0.16 ft (0.05 m) at Rosamond and 0.33 ft (0.10 m) at Lancaster to 0.49 ft (0.15 m) at Palmdale (Castle and others, 1984).

Generalized Hydrology

Antelope Valley has a predominantly arid climate, as evidenced by average annual precipitation of only 4.8 in. for the 1933-89 period of record at EAFB (Londquist and others, 1993). During the middle of the 1987-92 drought, total precipitation at Lancaster was 2.43 in. in 1989 and only 1.85 in. in 1990. Ground water is the primary local source of water for the valley. From 1983 to 1992, ground water supplied an average of about 60 percent of the total water used, with a maximum of about 75 percent in 1991 (Templin and others, 1994). The ground-water basin in Antelope Valley has been divided (Bloyd, 1967) into several subbasins separated by faults, outcrops, subsurface structural features, and physiographic boundaries (fig. 4). Most of the valley is underlain by the Lancaster ground-water subbasin, which is the most developed ground-water resource.

The aquifer system of the Lancaster subbasin consists of two alluvial aquifers—the principal and the deep aquifer—which are separated by a confining bed (Londquist and others, 1993). The principal aquifer is unconfined and overlies lacustrine clay sediments. The subsurface lithology of both aquifers has been logged as interbedded heterogeneous mixtures of clay, silt, sand, and gravel (Rewis, 1993). The deep aquifer is confined by a massive bed of blue clay, except in the northeastern part of Antelope Valley where the clay intersects land surface and thins to extinction (Durbin, 1978). The confining clay bed is at depths greater than 600 ft near Lancaster, which is in the south center of the Lancaster subbasin and surfaces between Redman and Buckhorn Lake. The principal aquifer extends to just north of the southern boundary of EAFB where the deep aquifer becomes unconfined in the northeastern part of the valley.

Mechanics of Aquifer-System Compaction

Land subsidence is the lowering of land-surface elevations over a long-term period and can be caused by various natural or human-induced processes, such as aquifer-system compaction. Aquifer-system compaction is the decrease in thickness of subsurface sediments that results from an increase in vertical compressive stress (Poland and others, 1972). Land subsidence usually is measured by differential leveling; aquifer-system compaction generally is measured by one or more types of gages installed at an extensometer well. The relation of compaction and associated subsidence to increases in effective stress that result from exceeding the preconsolidation stress of the aquifer materials has been documented in other locations (Epstein, 1987; Hanson, 1989), most notably in San Joaquin Valley (Poland, 1984). Total vertical stress at a particular depth in the aquifer system is a function of two opposing components and is expressed by the equation

$$p = p' + u, \tag{1}$$

where p is total vertical stress, p' is effective stress, and u is fluid stress. Total vertical stress, also called geostatic pressure or overburden, is the load on the aquifer matrix caused by the weight of aquifer-system materials and water above that point. Effective stress, p', is the grain-to-grain load and fluid stress, u, also called hydrostatic pressure or porewater pressure, represents the buoyant effect of water in the void spaces of the aquifer-system matrix. Because geostatic pressure is the sum of effective stress and porewater pressure, a decrease in porewater pressure will cause a corresponding increase in effective stress. If ground-water-levels decline, the release of porewater from fine-grained materials and the associated decrease in porewater pressure causes an equal increase in effective stress and usually will result in aquifer-system compaction.

Some of the compaction of sedimentary deposits is not permanent, but is recoverable and, thus, is referred to as elastic. If the reduction in porewater pressure and other factors are such that effective stress on the aquifer materials exceeds the previous maximum preconsolidation stress, permanent, nonrecoverable, inelastic compaction will occur. Preconsolidation stress is defined as the maximum antecedent effective stress of an unconsolidated sedimentary deposit and can be expressed as an

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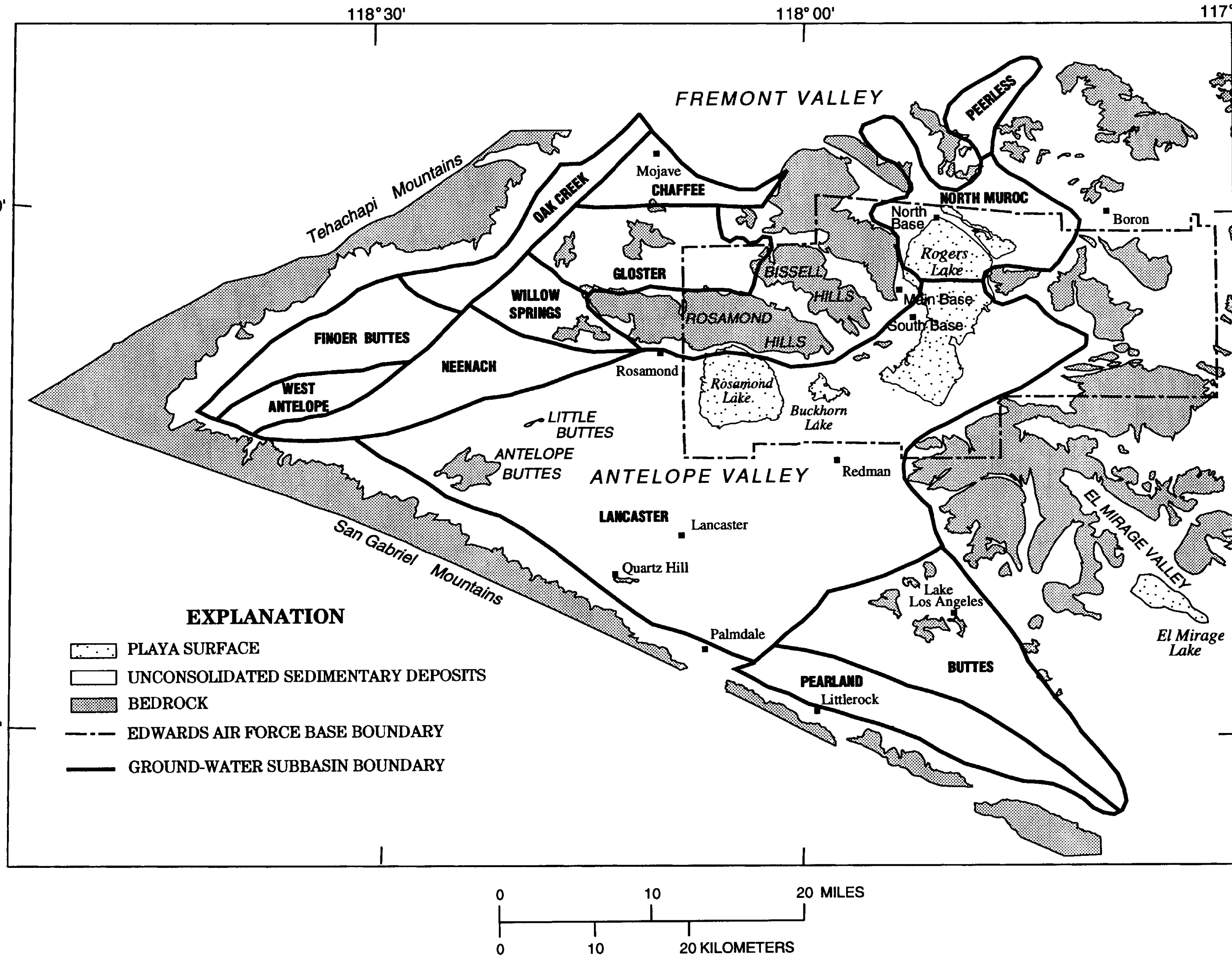

Figure 4. Generalized surficial geology and ground-water subbasins in Antelope Valley. (Modified from Londquist and others, 1993, fig. 4).

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equivalent hydrostatic hydraulic-head value. Where aquifer-system compaction is caused by ground-water-level declines, preconsolidation stress can be represented by the resultant of the previous minimum hydraulic head and geostatic pressure. Preconsolidation stress can be represented solely by the historical minimum hydraulic head if the geostatic load has remained constant during the stress period, the fine-grained interbeds are thin, or the influence of delayed drainage from thick interbeds is appropriately estimated. Preconsolidation stress is the threshold between elastic and inelastic aquifer-system compaction. If water levels decline but stay above this preconsolidation head, compaction will be in the elastic range. When water levels recover, compaction is reversed and water goes back into storage in fine-grained materials; thus, the elastic component of storage in fine-grained deposits is similar to storage in coarse-grained deposits. Water-level declines in coarse-grained sediments, such as sand, cause much smaller amounts of deformation because of the incompressible nature of coarse-grained sediments. Compaction in the inelastic range results in permanent loss of storage capacity and represents a one-time source of water.

The fine-grained deposits of alluvial and lacustrine origin are an integral part of the aquifer system in Antelope Valley. Although fine-grained deposits transmit water at a relatively low rate, the large total surface area of upper and lower surfaces of multiple fine-grained deposits interbedded with coarser sediments represents a significant intergranular storage capacity. This large total surface area, in combination with relatively high porosities of fine-grained materials, constitutes a major source of water for wells (Freeze and Cherry, 1979, p. 332). For example, throughout most of the western San Joaquin Valley, 20 to more than 60 percent of water pumped for irrigation from 1963 to 1966 was estimated to have come from inelastic storage of fine-grained deposits (Poland and others, 1975, p. H41; Williamson and others, 1989, p. D84).

Inelastic compaction and the resulting loss in storage capacity have detrimental effects on the aquifer system with respect to ground-water production. First, compaction results in a change in the bulk hydraulic properties of an aquifer system. Because the alluvial and lacustrine deposits in Antelope Valley are horizontally layered, the fine-grained deposits control, to a large extent, the vertical hydraulic conductivity of the aquifer system. Inelastic compaction results in decreased vertical hydraulic conductivity, which could result in increased confinement of underlying zones within the aquifer system. Increased confinement generally results in a smaller storage coefficient and corresponding lower yields. Secondly, compaction of the outermost surfaces of a fine-grained deposit effectively decreases the hydraulic connection to the interior part of the deposit, thus limiting access to the water in storage in these deposits (water of compaction).

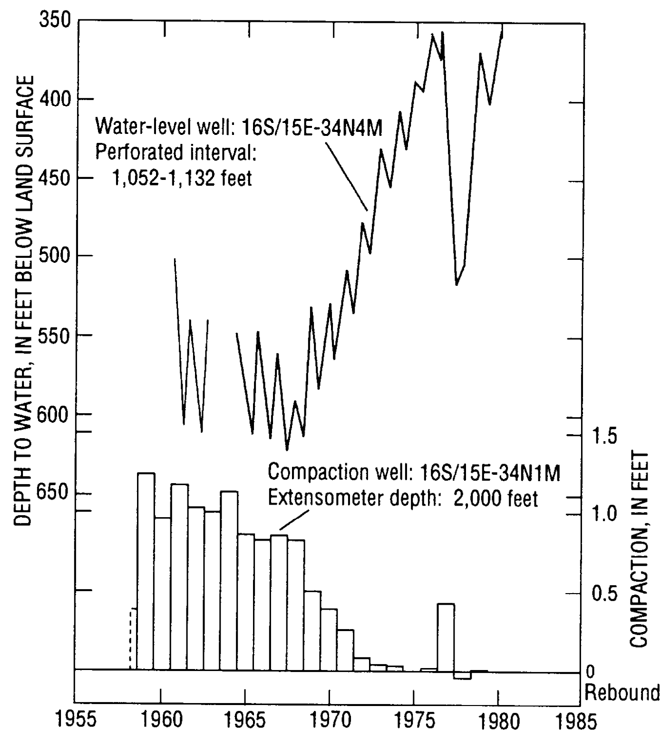

Figure 5. Measured water levels and compaction at a site near Mendota, San Joaquin Valley. (Modified from Ireland and others, 1984, fig. 21).

The detrimental effects of inelastic compaction described above and the overall loss of aquifer-system storage probably are best discussed with reference to data collected in San Joaquin Valley (Ireland and others, 1984, p. I22). Figure 5 shows the hydrograph of a well about 3 mi south of Mendota in western San Joaquin Valley (fig. 1) and measured compaction at an extensometer well in the immediate vicinity from part of 1958 through 1979. Original water-level declines between 1905 and 1960 were nearly 500 ft. Between 1960 and 1968, water levels were relatively stable and compaction averaged nearly 1.0 ft/yr. Deliveries of State Water Project water, which began in 1968, resulted in a drastic decrease in ground-water pumpage, a rapid recovery of water levels (270 ft) from 1968-76, and the elimination of measurable compaction by 1975. Substantial ground-water pumping resumed in 1977 in response to reduced deliveries from the State Water Project during the second of 2 severe drought years. Although ground-water pumpage increased to about three times the 1976 rate, it was less than one-third of the average annual rate for the 1961-68 period (Bertoldi, 1992, p. 71). This relatively low rate of ground-water pumpage resulted in 170 ft of

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drawdown and about 0.4 ft of inelastic compaction (fig. 5). The large drawdown (170 ft) associated with 1 year of relatively low ground-water pumpage and the subsequent rapid water-level recovery are attributed to the reduced storage capacity of the aquifer system caused by inelastic compaction.

The areal extent of compaction at a pumping well is partially dependent on the duration of pumping. Typically, the cone of depression that develops at a pumped well initially is narrow and the decline in water levels is fairly constant, but the rate of water-level decline gradually slows as the cone of depression spreads laterally. Similarly, the initial rates of subsidence often are high and then gradually slow. As the geographic influence of the cone of depression for a well enlarges, the lateral extent of the source of ground water supplied to the well also increases causing the area affected by aquifer-system compaction and land subsidence to become areally more extensive. Although compaction initially supplies water to an aquifer, it ultimately reduces the amount of water available from aquifer-system storage resulting in a more extensive spreading of the cone of depression, thus causing compaction farther from the well.

The number, thickness, and hydraulic conductivity of clay deposits, usually interbedded with coarse-grained aquifer material, influence not only the rate but also the duration of aquifer-system compaction. Large thickness and relatively low vertical hydraulic conductivity of the clay interbeds delay the equilibration of porewater pressures and effective stresses between the fine- and coarse-grained materials. Water levels measured in wells screened predominantly in the coarse-grained aquifer materials could recover to above preconsolidation-stress levels, but compaction in the aquifer system will continue until the stress in the fine-grained interbeds equilibrates with that in the coarse-grained deposits. Figure 5 illustrates the time-delay effect in San Joaquin Valley where compaction continued for almost a decade, even after a net rise in ground-water levels was measured during that same period. Equilibration of the stresses in all components of an aquifer system can take years or decades.

HISTORICAL PRECISE-LEVELING SURVEYS

Differential-Leveling Sources

Differential leveling has been done in some parts of Antelope Valley since before the turn of the century to ascertain changes in land-surface elevations, or lack thereof, relative to time. Most of the earliest leveling—for the first 50 years of this century—was done by national organizations as part of their original mission to establish and update large-scale vertical-control networks. Because of the nationwide scope of these surveys, relatively few bench marks were established in any one region. Densification—the establishment and measurement of a smaller-scale network of geodetic stations—was accomplished in the early 1950's by LAC for a vertical-control network located primarily in the southern half of Antelope Valley.

Most of the differential leveling data used in this report was from the LAC DPW Road Department's precise network surveying of Antelope Valley. This network was divided into five quads: Lancaster, Lancaster East, Lancaster West, Llano, and Palmdale (County of Los Angeles, 1980, 1981a, 1981b, 1981c, 1981d, 1981e, 1991). Second- or third-order standards of accuracy were achieved for these data. Other primary sources of differentially leveled elevations include the U.S. Department of Commerce, National Geodetic Survey, and the National Mapping Division (NMD) of the USGS, particularly for bench marks in areas not within LAC and leveled before 1955. Locations of selected leveling lines for each of these agencies are shown in figure 6. Most of the NGS leveling was first order and was published in NGS quads 341174, 341181, and 341184 (U.S. Department of Commerce, Coast and Geodetic Survey, 1966a, 1966b, 1966c), respectively, and a digital data base. Most of the NMD leveling was third order and was published in NMD quadrangles for California: Alpine Butte (160), Lancaster (161), Bouquet Reservoir (162), Rogers Lake (185), Rosamond (186), Willow Springs (187), Neenach (188), and Castle Butte (210) (USGS, National Mapping Division, 1955, 1974, 1969, 1973b, 1973c, 1976a, 1976b, 1973a, respectively).

Other sources of elevation data included third-order leveling done by the USGS, Water Resources Division, on EAFB in 1990 and 1991. In addition, elevation and subsidence-rate data were obtained from a report and map published by the LAC Engineer's office, which documented changes in land-surface elevation between 1928 and 1960 (Mankey, 1963). A more recent generalized comparison by LAC, DPW, Road Department of their bench-mark elevation data showed amounts of subsidence of more than 4 ft between 1957 and 1981 at two locations (Gerald Campbell, Los Angeles County, Department of Public Works, oral commun., 1992). For the 1957-81 period, subsidence ranged from 4.0 to 4.8 ft near downtown Lancaster, between 20th Street West and Division Street along Avenue I (Area 2, fig. 1) and from 3.5 to 4.9 ft between 70th and 90th Street East and between Avenues H and J (partly included in Area 3, fig. 1).

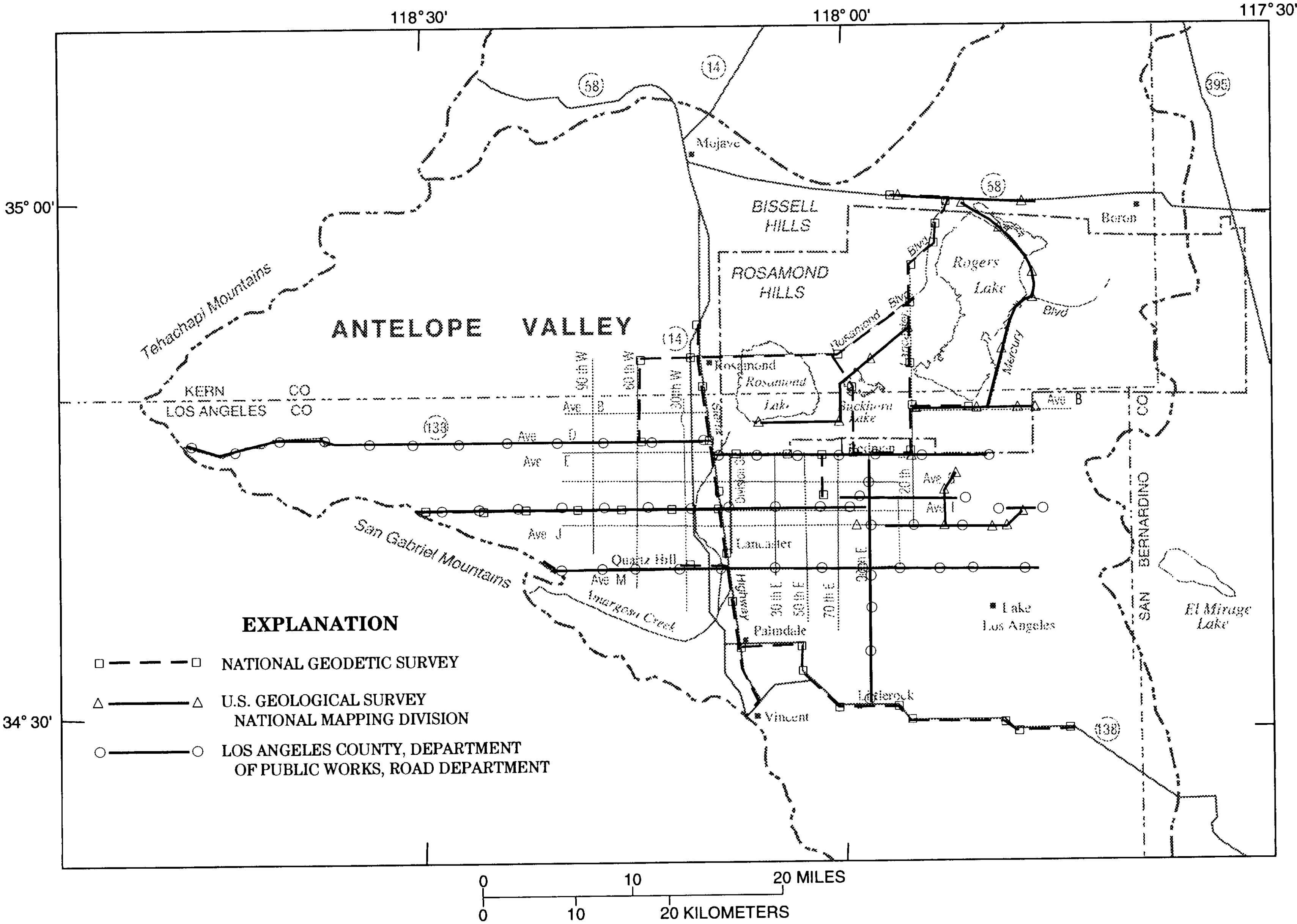

Figure 6. Selected leveling lines for surveys in Antelope Valley by the National Geodetic Survey, the U.S. Geological Survey National Mapping Division, and the Los Angeles County, Department of Public Works, Road Department.

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Accuracy and Limitations of Historical Leveling

The accuracy and precision of differential leveling at a regional scale are affected by several factors, including the validity and accuracy of the elevation of the origin bench mark; method of leveling, which is a component of the intended standards of accuracy; method of adjustment; and possible intrasurvey movement of control stations, which would influence the magnitude of misclosure. Because vertical-control stations in Antelope Valley are in networks of various scales and have been measured by several agencies with different objectives and standards of accuracy, differences in elevation of less than about 0.2 ft were considered to be "measurement error." To reduce some of the confusion caused by interagency leveling, two major leveling and adjustment programs, referenced to NGVD29, were done in the Southern California region in the last 25 years. McMillan (1973) reports,

> "By 1966, it had become apparent that, through the instability of the earth's surface and through the inclusion into the net of more and more interconnecting lines, the originally assigned elevations of the key bench marks were losing their validity...Leveling instituted by one agency could not be tied to leveling being done by another agency. As a result of these events, the Southern California Cooperative Leveling (COOP) Program was instituted in 1968-69, [and] resulted in a general readjustment of all primary leveling in Southern California [by NGS]."

Several years later, a similar program, Southern California Releveling Program (SCRP) also was coordinated by NGS. Leveling was done in 1978 and adjustments were completed in 1980 (U.S. Department of Commerce, National Geodetic Survey, 1980, digital data base). Because this was the most recent large-scale measurement of bench marks in Antelope Valley, elevations from this survey were used whenever possible for the primary vertical-control stations in the 1992 GPS survey.

A report by Mankey (1963) provides the oldest valleywide land-surface elevations for Antelope Valley. However, there seems to be an error in the data for bench mark US827 (no. *A*, fig. 7) at Sierra Highway and Avenue P in Palmdale. Because the report by Mankey (1963) was the source for estimates of subsidence at selected bench marks prior to 1960, the exclusion of some of its data and the rationale for that exclusion are discussed. On the basis of all data examined, the reported magnitude of 1.491 ft of subsidence between 1928 and 1960 appears to be in error because the 1960 land-surface elevation reported by LAC is questionable. On the basis of the location of bench mark US827 plotted on the subsidence-rate contour map and descriptions of the locations of bench marks published by NGS, it seems likely that bench mark US827 is also known as bench mark W425 1935. Bench mark US827 was reported as established in 1928, but bench mark W425 was not established until 1935; however, they appear to be the same bench mark because of the proximity of their locations and because of the earliest reported land-surface elevations of the two bench marks. Los Angeles County reported a land-surface elevation of 2,613.510 ft for bench mark US827 compared with the NGS-reported land-surface elevation of 2,613.446 for bench mark W425—a difference of only 0.064 ft. However, in contrast to the LAC 1960 reported elevation of 2,612.019, the NGS 1961 elevation is 2,613.643, a difference of 1.624 ft.

Other leveling done by NGS and LAC indicates that there was no apparent subsidence in the area near Sierra Highway between Avenues N-8 and Q during that time period (about 1930 to about 1961) nor more recently. Bench mark W425 was leveled five times by NGS between 1935 and 1961, and the differences in elevation are not indicative of subsidence; in fact, the change in elevation measured by NGS during that period was +0.197 (upward). Bench mark W425 was leveled also by LAC (five times) between 1957 and 1991 and likewise showed an upward change in elevation (of 0.277 ft). Elevation histories are available for 11 bench marks that are within 1 mi southward of bench mark W425, 7 bench marks that are within 1 mi northward, and 1 bench mark, BM 4217 (no. 149, fig. 7), 1.5 mi north of bench mark W425. Most of these bench marks were leveled seven times by NGS between 1935 and 1965. Rather than indicating subsidence, the elevation changes of these bench marks, including bench mark BM 4217, which was measured by leveling when reset in 1973 and measured by GPS in 1992, show increases in elevation (of less than 0.3 ft). Even if the elevations for bench mark US827 are correct, the amount and downward direction of land-surface change is not representative of this area with respect to the elevation histories of 19 other bench marks within 1.5 mi of the bench mark in question. Therefore, in extrapolating subsidence-rate information from the map by Mankey (1963), the contours of equal rates were redrawn ignoring bench mark US827 and no estimates of subsidence were made in the area where the published and redrawn contour lines showed divergence.

There was some concern that the bench marks used as primary vertical-control stations for LAC networks (those that were common to adjacent quads) might have been subject to land subsidence. However, the possibility was slight because the

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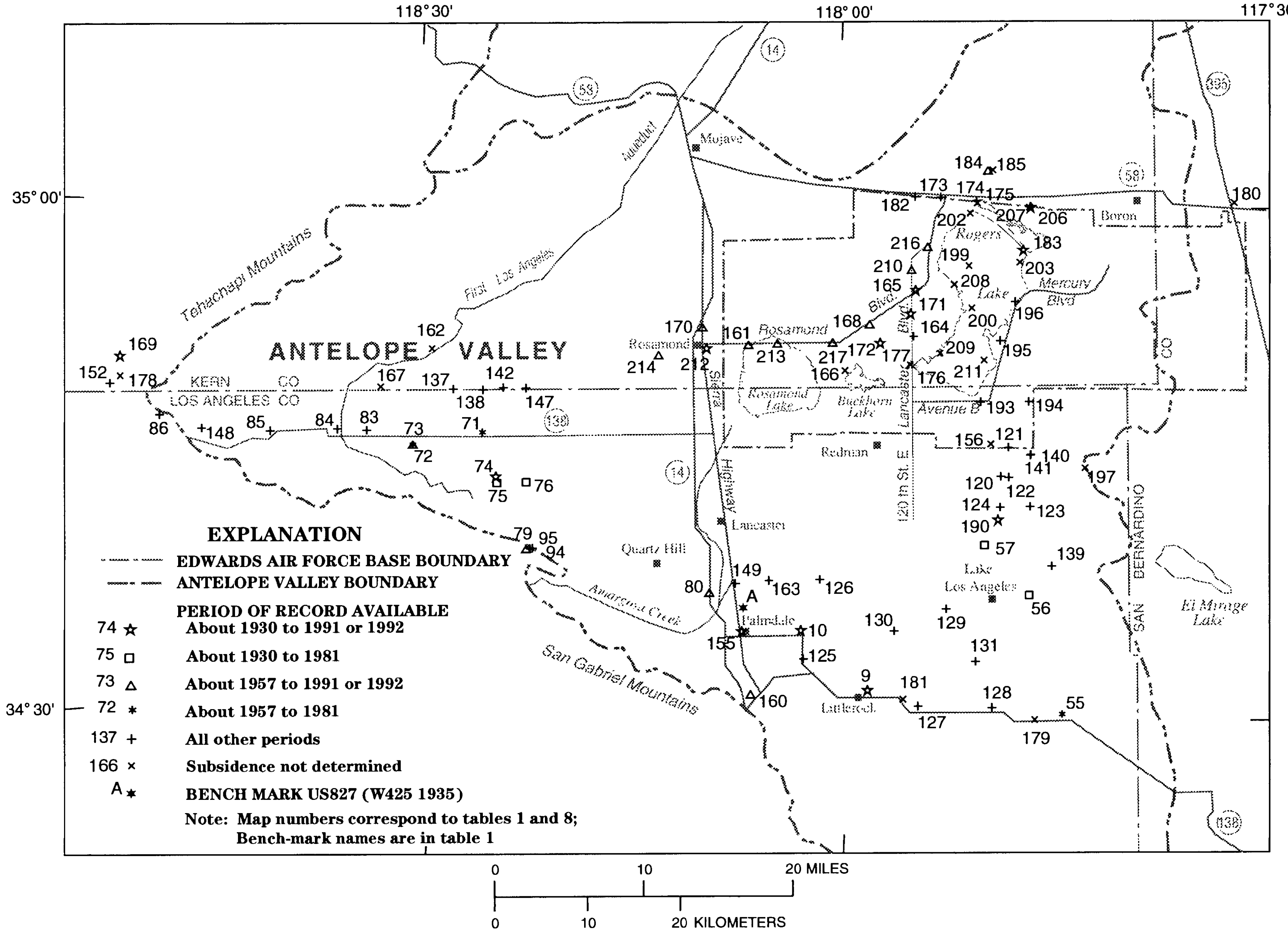

Figure 7. Locations of selected bench marks in Antelope Valley at which subsidence has been 1 foot or less.

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selection of these bench marks for control was based on the results of a least squares analysis. Bench marks with the least amount of change in elevation between periods of leveling had been selected as primary vertical-control stations for their network. Nonetheless, one of the goals of the GPS measurement was to evaluate whether a significant amount of subsidence had been ignored because these bench marks had been held fixed. These vertical-control stations were BM 1327 (no. 79, fig. 7) and BM 4219 (no. 151, fig. 8) in the Palmdale quad (Gerald Campbell, Los Angeles County, Department of Public Works, oral commun., 1992). Because of poor visibility or accessibility at both bench marks, BM 1327 and BM 4219, bench marks BM 2076 (no. 94, fig. 7), BM 471 (no. 23, fig. 8), and BM 4217 (no. 149, fig. 7) were instead selected for the GPS network. BM 2076 is 0.5 mi east of BM 1327 near Elizabeth Lake (fig. 1). During one GPS multiple-constraint adjustment, the elevation of BM 2076 was not held fixed, and the computed elevation was within a few millimeters of the 1991 leveled elevation, indicating that significant vertical crustal movement had not occurred. Thus, this bench mark was shown to be acceptable for use as a primary vertical-control station in the GPS network. On the basis that conditions were similar—no significant vertical crustal movement—0.5 mi away, it was assumed that BM 1327 also was suitable as a primary vertical-control station for a leveling network.

Vertical-control station BM 4219 (no. 151, fig. 8) on Avenue M was bracketed by two substitute bench marks in the GPS network because it seemed to be near a boundary between a subsiding area (Area 2, fig. 1) and a nonsubsiding area. BM 4217 (no. 149, fig. 7) is 1.4 mi south of BM 4219 along Sierra Highway near Avenue N-8, and BM 471 (no. 23, fig. 8) is 0.75 mi north of BM 4219 near Avenue L-4, toward the area of subsidence. The difference between the 1991 leveled elevation and the 1992 GPS-derived orthometric height for BM 4217 was insignificant (0.04 ft). The difference of 0.13 ft for BM 471 for the same period was an order of magnitude larger, but still within the ±0.2 ft range considered to be measurement error. On the basis of these relatively insignificant differences between GPS-derived and leveled elevations of these bracketing bench marks, BM 4219 has not experienced sufficient subsidence to necessitate revising elevations of bench marks in the LAC networks that have been dependent on the elevation of this vertical-control station.

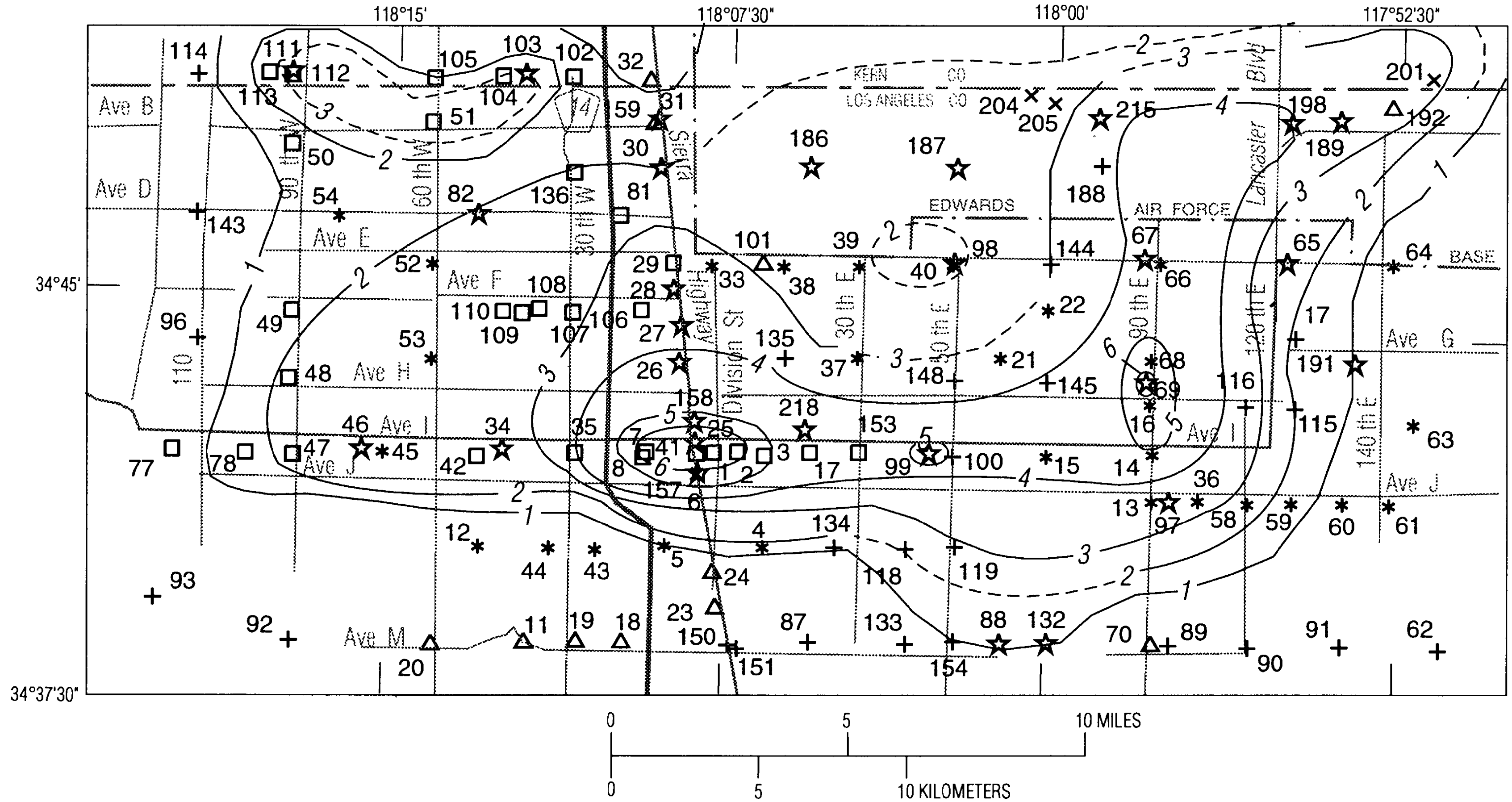
Increases and decreases in land-surface elevations for periods of decades that are attributed to tectonic causes have been documented for Southern California, including the Palmdale area (Castle and others, 1984). In assessing the amount of crustal movement related only to tectonic causes, Castle and others (1984) estimated the amount of subsidence that they could attribute to fluid withdrawal and eliminated it to obtain the resultant land-surface profiles. In contrast to other areas in Southern California, tectonic-induced crustal deformation within the western Mojave Desert block was relatively uniform, with a slight downward-to-the-north tilt between Palmdale and Rosamond relative to profiles of previous years. A difference in elevation of 0.20 ft (0.06 m) across the valley in a north-south orientation between 1959 and mid-1971 (Castle and others, 1984, fig. 62) to a maximum difference of 0.30 ft (0.09 m) after the post-1974 collapse can be inferred from their maps (Castle and others, 1984, fig. 65).

The tectonic influence on leveling predominantly within Antelope Valley, such as that done for the LAC networks, most likely would be affected only by this downward tilt of between 0.2 and 0.3 ft and to a lesser extent than indicated by Castle and others (1984) because LAC leveling did not extend north of the Los Angeles/Kern County line, which is 3 mi south of Rosamond. On the other hand, all NGS leveling originated at a tidal station bench mark in San Pedro (fig. 1); thus, their elevations would have incorporated the amounts of tectonic uplift relative to the 1955 time datum to a maximum of 1.15 ft (0.35 m) in about 1973 (Castle and others, 1984, fig. 63).. However, relatively few of the calculations in this report include NGS data for bench marks in LAC from the post-1955 period, and variations in the relatively uniform valleywide uplift can be incorporated into the ±0.2 ft allowed for measurement error. Therefore, calculations of subsidence resulting from artificially induced compaction have not been adjusted to account for crustal movement--subsidence or uplift—presumed to result from tectonic or "natural" causes.

GLOBAL POSITIONING SYSTEM GEODETIC SURVEYING FOR LAND-SUBSIDENCE MONITORING

Principles of Global Positioning System Geodetic Surveying

Geodetic measurements made by receiving and recording radio signals sent by GPS satellites have been shown to be very accurate relative to other systems of geodetic measurement (Dixon, 1991), particularly when relatively large areas are involved. Geodetic measurements are those made to high standardized levels of accuracy and corrected for the curvature of the Earth's surface. In geodetic networks, the unknown coordinates of stations are determined by relating them to points with known coordinates (control stations) using instruments that can achieve the intended standards of accuracy. The three-dimensional position of a point or station



EXPLANATION

—2— — LINE OF EQUAL MAGNITUDE OF SUBSIDENCE, IN FEET - Dashed where approximately located. Interval 1 foot

PERIOD OF RECORD AVAILABLE

74	☆	About 1930 to 1991 or 1992 (Code 'A' in table 8)
75	□	About 1930 to 1981 (Code 'B' in table 8)
73	△	About 1957 to 1991 or 1992 (Code 'C' in table 8)
72	*	About 1957 to 1981 (Code 'D' in table 8)
137	+	All other periods (Code 'E' in table 8)
204	×	Subsidence not determined

Note: Map numbers correspond to tables 1 and 8; Bench-mark names are in table 1

Figure 8. Magnitude of calculated or estimated subsidence from about 1930 to 1992 in central Antelope Valley.

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on Earth is computed on the basis of the distance or range to each observed satellite whose position within its orbit is known. In relative positioning, two or more GPS receivers receive signals simultaneously from the same set of satellites. These observations are processed to obtain the three-dimensional components of a vector between each pair of observed stations. The vector coordinates, d*x*, d*y*, and d*z*, represent the relative positions of the stations and are based on an earth-centered Cartesian coordinate system. GPS-computed horizontal and vertical coordinates are referenced to the universally accepted ellipsoid, GRS80 (Geodetic Reference System 1980), that currently best approximates the Earth's shape. These coordinates usually are converted into other, more familiar, coordinate systems.

The selection of a set of horizontal-control stations and a set of vertical-control stations, each referenced to its respective datum, defines the three-dimensional, localized reference system to which GPS coordinates are converted. Stations whose horizontal positions had been measured previously are known as horizontal-control stations. Commonly, "vertical-control station" and "bench mark" are synonymous. In this report, "primary vertical-control stations" are those that are at stable locations relative to areas susceptible to artificially induced compaction and whose previously measured elevations were held fixed in the GPS-network adjustment. Other stations, whose elevations have changed and probably will continue to change with time as determined by repeat measurements, will be considered "secondary vertical-control stations." "Bench marks" will be used to refer to either or both types of vertical-control stations.

In this report, GPS data have been converted to latitude and longitude for the horizontal coordinates and elevation above mean sea level for the vertical coordinate. Latitude and longitude have been referenced to another ellipsoid that best represents the Earth's surface in this locality, which is the North American Datum 1983, generally called NAD83. The conversion of GPS-measured horizontal coordinates to latitude and longitude is a straightforward mathematical transformation. However, the conversion of the GPS-measured vertical coordinate, ellipsoidal height, to a locally valid elevation is more complex. A closer approximation of the local vertical reference system (datum), which is referenced to mean sea level, is achieved by modeling the difference (geoidal separation) between the ellipsoid (NAD83 datum) and the geoid, an equipotential surface that is equivalent to mean sea level. These relations (fig. 9) are expressed by the equation

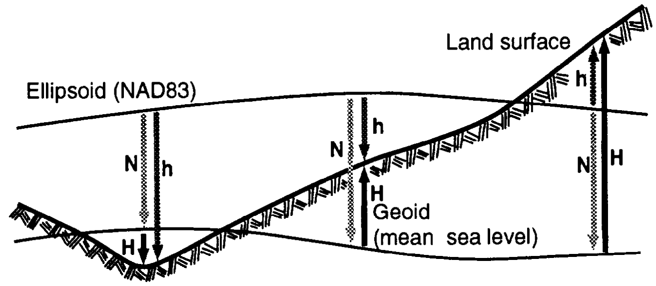

Figure 9. Examples of the relations of land-surface, ellipsoidal, and geoidal heights in North America.

$$H = h - N, \qquad (2)$$

where

H is the land-surface elevation, referenced to the geoid or mean sea level;
h is the ellipsoidal height, referenced to the ellipsoid; and
N is the geoidal separation, also referenced to the ellipsoid.

Where the geoid surface is below the ellipsoid, as shown in figure 9, *N* has a negative value. For example, 725.890 m –(-31.889 m) yields an elevation of 757.779 m for bench mark BM 471 (no. 23, fig. 8). GPS-computed elevations are referred to as orthometric heights.

Surface gravity and conventional differential-leveling measurements are used to estimate geoidal separations. The NGS geoid model GEOID90 (Milbert, 1991) was used in the GPS-based elevation calculations for this study. This model was evaluated on a 3-minute × 3-minute regular grid that spans the conterminous United States. Data from four different grids were used as input data to the GEOID90 model: OSU89B (Ohio State University 1989) geoid heights and OSU89B gravity anomalies, gravity anomalies gridded from 1.5 million points, and topographic elevations. OSU89B is a spherical harmonic model of the Earth's geopotential with a resolution to about 50 km (31 mi). A sample of elevations simulated by the GEOID90 model compared favorably with first-order leveling, with a root mean square error (RMSE) of 0.01 m (0.0328 ft) between points spaced at 10 km (6.2 mi) (Milbert, 1991). Given the distance of about 60 mi (100 km) between the eastern and western extremes of Antelope Valley, the maximum error associated with orthometric heights because of the geoidal-height estimation would be about 0.3 ft (0.1 m).

Selection of Primary Control Stations

A large-scale monitoring network of bench marks was established and measured in Antelope Valley during 1992 to calculate historical subsidence and to provide a basis for comparisons with future measurements. Existing geodetic stations in the study area were evaluated for their suitability for inclusion in the network. All selected bench marks have clear overhead visibility to facilitate measurement by GPS, which will allow precise comparative measurements to be made in the future. Stations in the Antelope Valley subsidence network (fig. 10, table 2) were selected for various purposes. Primary control stations in a geodetic network are stations with horizontal coordinates or elevations or both that have been accurately measured previously and currently are considered reliable. The three criteria for selection of primary horizontal- and vertical-control stations were (1) areal distribution in the study area, (2) level of accuracy of previous measurements, and (3) stability of the Earth's surface near each station.

After the geographic scope of the GPS network was tentatively defined, diagrams of horizontal-control stations published by NGS and NMD were examined. Areally distributed control stations that had the most accurate levels of measurement were selected to minimize error introduced to the new coordinates of secondary control stations computed by relative positioning methods. The Federal Geodetic Control Committee (1989) defined six orders of accuracy that are applicable to GPS surveys, which include, in order of decreasing accuracy, AA, A, B, first, second, and third. Stations in the California HPGN, which was newly established and surveyed in 1991 using GPS, have horizontal coordinates that meet or exceed order B accuracy [±(8 mm + 1 ppm)]. Coordinates of other horizontal-control stations, measured by conventional geodetic methods, have first-, second-, or third-order standards of accuracy. The accuracy of horizontal coordinates is important even for GPS surveys in which determination of the vertical component is of primary concern because the vertical reference system is related to the horizontal datum—the reference ellipsoid.

Generally, 10 percent of a network should consist of primary control stations, which, for a network of 85 stations, would be 8 or 9 stations for horizontal control and 8 or 9 stations for vertical control (Ellis Veatch, Ashtech, Inc., written commun., 1991). Eight horizontal-control stations originally were selected for the network, but one station, BULL (no. 167, fig. 10), in the western part of the valley was omitted as a primary control station. Computations during a preliminary GPS multiple-constraint adjustment revealed that holding fixed the coordinates of this station, which originally was measured to only third-order standards of accuracy, introduced an unacceptably large error in the constrained adjustment.

Seven horizontal-control stations were selected for the Antelope Valley GPS network. Six stations are distributed around the perimeter of the study area and one is centrally located within the study area. Four HPGN stations are near the boundaries of Antelope Valley. Stations HPGN 0618, HPGN 0705, and HPGN PEARBLOSSOM (nos. 178, 179, and 181, respectively, fig. 10) were horizontal-control stations in the 1992 GPS survey. Station HPGN 0805 (no. 180, fig. 10) was occupied (observed) by a surveyor, but was not used for horizontal control because it was relatively distant from the other Antelope Valley network stations and thus would have introduced too much proportional error into the control. The horizontal coordinates of station PEARBLOSSOM have an order A standard of accuracy [±(5 mm + 0.1 ppm)]; the three other HPGN stations are order B accuracy. Areal distribution of the three high-precision stations selected for horizontal control is limited. HPGN 0705 and HPGN PEARBLOSSOM (nos. 179 and 181, respectively, fig. 10), which are only about 9 mi (14.5 km) apart, are both at the southeast boundary of the valley. Station HPGN 0618 (no. 178, fig. 10) is at the western apex of Antelope Valley. To provide control for the north and east boundaries and within the network, four additional horizontal-control stations were selected on or near EAFB. These stations were selected because they had been measured using GPS during a previous study (Blodgett and Williams, 1992). The four additional horizontal-control stations are (map number, alternate name, if any, and order of accuracy are in parentheses) ALDER 1947 (no. 161; first), GRINELL Reset 1929 (no. 156, BM 5190; first), JUNCTION 1958 (no. 182; first), and OBAN 1929 LINT (no. 28, BM 479; second) (fig. 10).

The most important criteria for selecting primary vertical-control stations for a land-subsidence study is their vertical stability. Rock outcrops and other evidence of near-surface bedrock usually represent locations that are not subject to land subsidence and thus are ideal sites for control stations. Examination of geologic maps (Dibblee, 1960, 1963) and communication with earth scientists familiar with Antelope Valley (Devin Galloway, USGS, oral commun., 1992) verified areas that were presumed to be stable because of their geologic foundation. Bench-mark descrip-

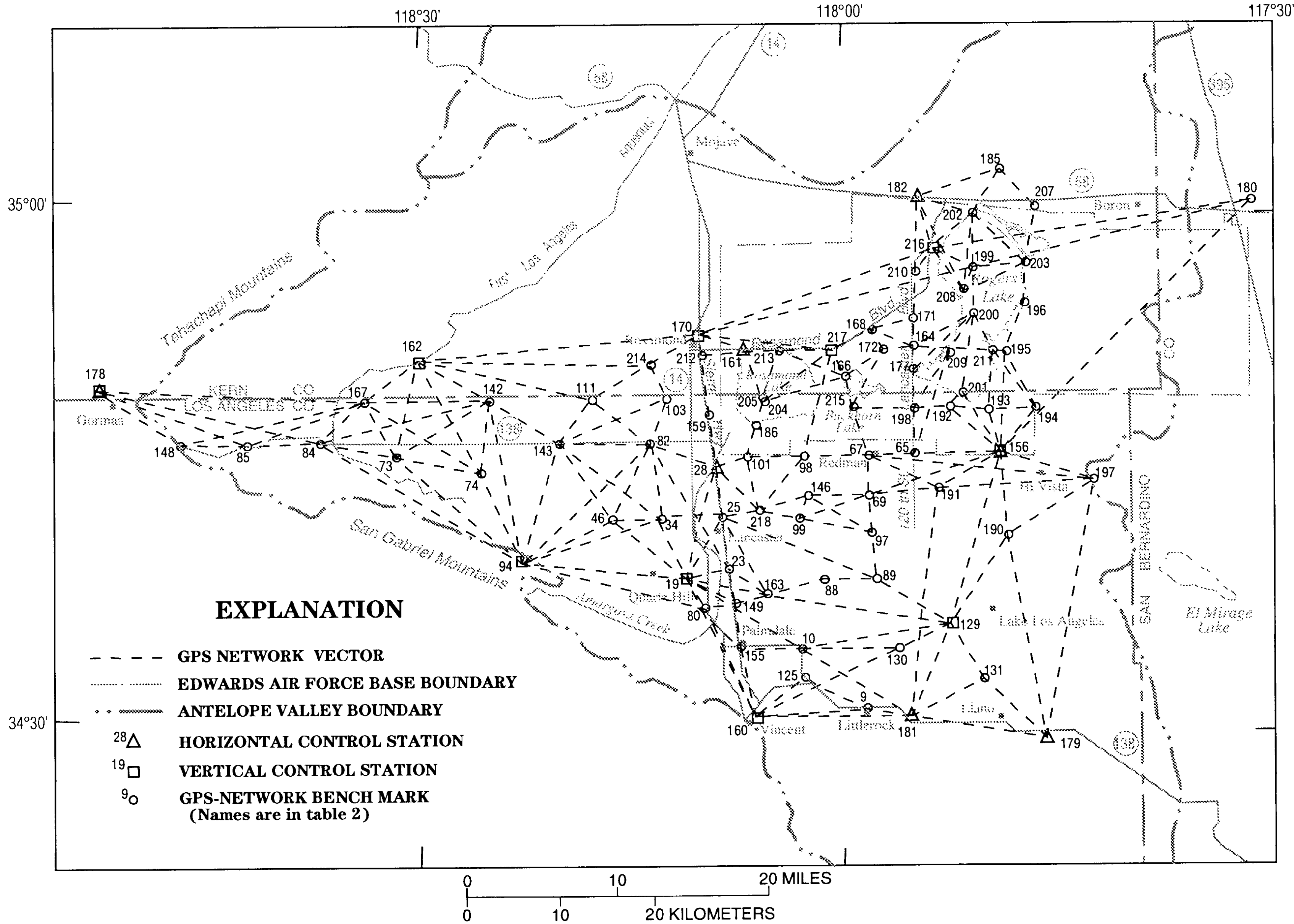

Figure 10. Selected vectors and 85 geodetic stations in Antelope Valley subsidence network measured using Global Positioning System surveying, 1992.

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Table 2. Global Positioning System code name, elevation, standard error, geoidal height, and ellipsoidal height from multiple-constraint adjustment of 85 stations measured in 1992 by Global Positioning System geodetic surveying in Antelope Valley, Los Angeles and Kern Counties

[Map numbers refer to bench-mark locations in figures 7 or 8. Elevations are referenced to NGVD29. Ellipsoidal heights are referenced to the NAD83 ellipsoid. 1σ, 1 standard error; ft, foot; m, meter. ND, not determined]

Map No.	Bench-mark name	GPS code name	Elevation (ft)	Elevation (m)	Elevation 1σ (m)	Geoidal height (m)	Ellipsoidal height (m)
9	BM 135	306H	2,936.066	894.869	0.009	-31.619	863.250
10	BM 171	306E	2,615.063	797.032	.010	-31.832	765.200
19	BM 336	489E	[1]2,520.137	768.100	ND	-31.911	736.187
23	BM 471	_B57	2,486.274	757.779	.008	-31.979	725.799
25	BM 474	2335	2,330.610	710.335	.006	-32.042	678.292
28	BM 479	OBAN	2,302.886	701.885	.006	-32.020	669.865
34	BM 537	_537	2,329.413	709.970	.008	-31.985	677.985
46	BM 823	306B	2,375.875	724.131	.008	-31.956	692.175
65	BM 1159	6116	2,356.589	718.253	.006	-31.959	686.284
67	BM 1165B (Offset)	O122	2,338.980	712.886	.005	-32.026	680.860
69	BM 1171A	1171	2,382.089	726.025	.007	-32.030	693.995
73	BM 1276	1276	2,880.411	877.906	.010	-31.793	846.113
74	BM 1290	1290	2,782.591	848.092	.011	-31.850	816.242
80	BM 1380	1380	2,640.123	804.670	.006	-31.868	772.801
82	BM 1469	AVEN	2,367.370	721.539	.006	-31.948	689.591
84	BM 1483	1483	3,051.102	929.930	.010	-31.729	898.201
85	BM 1494	1494	3,143.875	958.206	.008	-31.607	926.599
88	BM 2030	2030	2,486.914	757.974	.009	-31.973	726.001
89	BM 2037	2037	2,532.858	771.977	.007	-31.924	740.053
94	BM 2076	2076	[1]3,415.129	1,040.880	ND	-31.766	1,009.114
97	BM 2169	2169	2,445.419	745.327	.009	-31.989	713.337
98	BM 2174	6130	2,318.073	706.514	.006	-32.062	674.451
99	BM 2180	2180	2,382.233	726.069	.009	-32.071	693.997
101	BM 2186	154F	2,301.344	701.415	.006	32.037	669.377
103	BM 2235	2235	2,343.951	714.401	.009	-31.879	682.522
111	BM 2317	2317	2,431.770	741.167	.009	-31.857	709.310
125	BM 2616	2616	2,705.720	824.663	.009	-31.752	792.911
129	BM 2706	2706	[1]2,799.291	853.182	ND	-31.771	821.411
130	BM 2716	2716	2,687.189	819.015	.009	-31.770	787.245
131	BM 2746	2746	2,889.050	880.539	.010	-31.651	848.888
142	BM 3549	3549	2,593.805	790.553	.012	-31.820	758.733
143	BM 3636	3636	2,487.622	758.190	.007	-31.906	726.284
146	BM 3738	3738	2,356.317	718.170	.009	-32.081	686.089
148	BM 4116	973X	3,329.376	1,014.744	.008	-31.510	983.234
149	BM 4217	811W	2,577.017	785.436	.006	-31.925	753.511
155	BM 5159	2657	2,658.759	810.350	.007	-31.811	778.539
156	BM 5190	GRNL	[1]3,173.916	967.362	ND	-31.757	935.604
159	BM 5204	ON48	2,304.723	702.445	.009	-31.926	670.518
160	BM 5205	899M	[1]3,085.214	940.327	ND	-31.621	908.706
161	ALDER 1947	ALDR	2,274.728	693.303	.005	-31.790	661.513

Footnote at end of table.

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Table 2. Global Positioning System code name, elevation, standard error, geoidal height, and ellipsoidal height from multiple-constraint adjustment of 85 stations measured in 1992 by Global Positioning System geodetic surveying in Antelope Valley, Los Angeles and Kern Clunties--*Continued*

Map No.	Bench-mark name	GPS code name	Elevation (ft)	Elevation (m)	Elevation 1σ (m)	Geoidal height (m)	Ellipsoidal height (m)
162	Aqueduct 100	A100	[1]3,126.299	952.849	ND	-31.569	921.280
163	ARP 1971 PMD	PARP	2,505.363	763.597	0.007	-31.956	731.640
164	Ask P7	7ASK	2,336.490	712.127	.005	-31.782	680.345
166	BUCKHORN 3 1967	BKHN	2,401.001	731.789	.006	-31.877	699.912
167	BULL	BULL	2,861.378	872.105	.010	-31.702	840.403
168	D1155 1961	155D	2,378.070	724.800	.006	-31.729	693.071
170	F1147 1961	147F	[1]2,447.581	745.986	ND	-31.734	714.252
171	GWM2 1937	GWM2	2,302.203	701.677	.006	-31.719	669.958
172	GWM4 1937	GWM4	2,322.493	707.861	.006	-31.794	676.067
177	H1155 1961 OS89	O55H	2,275.699	693.599	.007	-31.848	661.751
178	HPGN 0618	0618	[1]3,641.872	1,109.988	ND	-31.141	1,078.847
179	HPGN 0705	0705	3,480.595	1,060.833	.009	-31.385	1,029.448
180	HPGN 0805	0805	2,473.901	754.008	.042	-31.311	722.696
181	HPGN PEARBLOSSOM	PEAR	3,027.095	922.613	.006	-31.564	891.049
182	JUNCTION 1958	JUNC	2,375.812	724.112	.006	-31.482	692.630
185	LC68 1952 OS89	OC68	2,511.620	765.504	.008	-31.441	734.062
186	LS38 1929	LS38	2,283.721	696.044	.006	-31.980	664.063
190	LS46 1929	LS46	2,775.960	846.071	.009	-31.767	814.304
191	LS53 1929	LS53	2,415.841	736.312	.009	-31.915	704.397
192	M1155 1961	155M	2,297.492	700.241	.006	-31.871	668.369
193	MDC4 1973	MDC4	2,332.159	710.807	.006	-31.802	679.005
194	MDC6 1973	MDC6	2,602.277	793.135	.008	-31.709	761.426
195	MDC30 1973	MD30	2,291.619	698.451	.007	-31.751	666.699
196	MDC33 1973	MD33	2,278.816	694.549	.009	-31.670	662.878
197	MONDAY RS1929	MOND	3,175.284	967.779	.008	-31.635	936.143
198	P1155 1961	155P	2,308.539	703.608	.007	-31.922	671.685
199	Rogers Lakebed 1	RLB1	2,270.965	692.156	.007	-31.622	660.534
200	Rogers Lakebed 3	RLB3	2,271.913	692.445	.007	-31.715	660.730
201	Rogers Lakebed 4	RLB4	2,269.068	691.578	.008	-31.838	659.739
202	Rogers Lakebed 5	RLB5	2,274.430	693.212	.006	-31.534	661.678
203	Rogers Lakebed 6	RLB6	2,280.194	694.969	.007	-31.590	663.379
204	ROSAMOND	3631	2,272.802	692.716	.008	-31.909	660.806
205	Rosamond Lake 1	ROL1	2,274.367	693.193	.006	-31.922	661.271
207	RS38 1932 OS89	O38R	2,315.075	705.600	.010	-31.498	674.102
208	Santa Fe Trail 1	SFT1	2,276.247	693.766	.006	-31.667	662.099
209	Sewage Treatment Pond 1	STP1	2,278.734	694.524	.007	-31.813	662.701
210	T1139 1961	139T	2,448.733	746.337	.008	-31.611	714.726
211	Transect 8	TRN8	2,271.477	692.312	.006	-31.789	660.522
212	U56 1926	_U56	2,326.027	708.938	.007	-31.795	677.143
213	U1154 1961	154U	2,273.944	693.064	.008	-31.787	661.277
214	V1146 1961	146V	2,363.830	720.460	.009	-31.800	688.660
215	V1155 1961	155V	2,296.183	699.842	.007	-31.969	667.873
216	Y1139 1961	139Y	[1]2,369.756	722.265	ND	-31.570	690.695
217	Y1154 1961	154Y	[1]2,408.452	734.060	ND	-31.787	702.273
218	Z488 1955	488Z	2,362.144	719.946	.007	-32.072	687.874

[1]Vertical-control station elevation held fixed in adjustment.

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tions were searched to find bench marks constructed on bedrock outcrops or in areas where bedrock is near land surface. Historical-leveling data also were reviewed to confirm the stability of these stations and to search for additional bench marks that showed insignificant changes in elevation during the course of several decades. Ten bench marks were selected as primary vertical-control stations for the Antelope Valley GPS network: Aqueduct 100 (no. 162 on fig. 10), F1147 1961 (no. 170), HPGN 0618 (no. 178), Y1139 1961 (no. 216), Y1154 1961 (no. 217), BM 336 (no. 19), BM 2076 (no. 94), BM 2706 (no. 129), BM 5190 (no. 156), and BM 5205 (no. 160) (fig. 10).

The stability of the Earth's surface is of concern in the selection of primary horizontal- and vertical-control stations. Because two of Antelope Valley's boundaries are at, or at least parallel to, fault zones, the potential influence of tectonic activity was considered. Control stations close to the San Andreas Fault zone (fig. 2) are, from east to west, HPGN 0705 (no. 179), HPGN PEARBLOSSOM (no. 181), BM 5205 (no. 160), BM 2076 (no. 94), and HPGN 0618 (no. 178) (fig. 10). HPGN 0618 is near the intersection of the San Andreas and Garlock Fault zones.

Because the motion of the San Andreas Fault is related to strike-slip (lateral) rather than thrust (vertical) forces, changes in the horizontal coordinates are of more concern than changes in vertical coordinates. In the absence of significant tectonic activity in the fault zone between the time of the original GPS measurement (summer 1991) and the time of this GPS survey (spring 1992), the horizontal coordinates of the California HPGN stations were considered reliable and accurate for the 1992 adjustment. HPGN PEARBLOSSOM is a National Crustal Motion Network (NCMN) site also and often is used in post-earthquake crustal-movement studies, such as was done in May 1992 following the Landers earthquake (Charles Peer, Los Angeles County, Department of Public Works, oral commun., 1992). In the future, should crustal motion affecting the horizontal coordinates be suspected, the HPGN and NCMN stations would be reobserved by a consortium of governmental and educational agencies and updated coordinates would be made available.

Tectonic activity in Antelope Valley, not necessarily resulting directly from earthquakes, contributes to uncertainty in bench-mark elevations and thus to uncertainty in current and future estimates of land subsidence. Maximum changes in land-surface elevations in Antelope Valley that were attributed to tectonic sources and that occurred prior to 1978 were about 1.15 ft (0.35 m) (Castle and others, 1984, 1987). The most recent first-order leveling that included the majority of the vertical-control stations selected for the subsidence-monitoring network was done in 1978 and was adjusted in 1980 by NGS. This and all other historical leveling examined by Castle and others for evidence of tectonic-based vertical crustal movement originated at the San Pedro (fig. 1) tidal and vertical-control station to ensure that all elevations were referenced to the same regional vertical datum.

Localized leveling within Antelope Valley only, such as that done by LAC, would tend to minimize the problem of a shifting vertical datum because all bench marks in the network would be part of the same tectonic environment. Thus, changes in elevations based only on a local datum with vertical-control stations stable relative to artificial compaction would be virtually unaffected by uplift or collapse that was more or less uniformly distributed throughout the valley, as it appears to have been in the two documented periods of land surface instability resulting from tectonic activity.

A comparison between bench-mark elevations leveled and adjusted by NGS in 1961 and in 1978 affirms the phenomenon of tectonic uplift. For this current study (1992), 1961 was selected for the comparison for two reasons. First, elevations of vertical-control stations in the 1989 GPS survey in the vicinity of EAFB were referenced to a 1961 datum. This datum also had been used for 1973 leveling in that vicinity, so the use of the 1961 datum for the 1989 study allowed comparisons to be made among the three data sets without introducing uncertainties from network adjustments and tectonically induced changes. Secondly, 1961 was selected for this comparison because leveling was done just prior to or very close to the time when the tectonically based uplift is postulated to have become measurable in Antelope Valley (Castle and others, 1984). Because this period of uplift is thought to have ended in 1974, the near-maximum differences in elevation could be crudely estimated by comparing the 1978 with the 1961 elevations of bench marks considered to be on stable ground relative to compaction-induced subsidence.

Differences in elevations were calculated for a 17-year period (1961-78) (table 3) for vertical-control stations F1147 1961 (no. 170), BM 5205 (M899 1955; no. 160), Y1139 1961 (no. 216), Y1154 1961 (no. 217) (fig. 10), and F54 1926 (no. 169, fig. 7) from which the elevation of HPGN 0618 (no. 178, fig. 10) was subsequently determined (table 3). Differences range from +0.079 to +0.548 ft and correspond with elevation data presented by Castle and others (1984), which indicate that the greatest uplift in this area is near the San Gabriel Mountains. The average difference in elevation for two of the primary vertical-control stations, F1147 1961 and Y1139 1961, which were

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Table 3. Elevations measured in 1961 and 1978 and the change in elevation for selected bench marks in Antelope Valley

[Elevations are referenced to NGVD29. Source of data: 1961 elevations, U.S. Department of Commerce, Coast and Geodetic Survey (1966b, 1966c); 1978 elevations, Emery Balasz (National Geodetic Survey, oral commun., 1992). ft, feet]

Bench-mark name	Elevation (ft)		Change in elevation (ft)
	1961	1978	
F1147 1961	2,447.328	2,447.581	+0.253
M899 1955	3,084.974	3,085.214	+.240
Y1139 1961	2,369.677	2,369.756	+.079
Y1154 1961	2,408.361	2,408.452	+.091
F54 1926	3,463.274	3,463.822	+.548

control stations in the 1989 GPS network also, is +0.17 ft. A cursory examination of orthometric heights computed for bench marks measured in the 1989 (Blodgett and Williams, 1992) and the 1992 GPS surveys indicates that many of the 1992 values are higher by 0.1-0.2 ft than those for 1989.

The effect of tectonic activity between 1978 and 1992 on the accuracy of the elevations of the primary vertical-control stations is unknown. On the basis of historical tectonic episodes documented in southern California, the magnitude of tectonically related elevation changes in Antelope Valley probably would not exceed 1.15 ft (0.35 m); however, a change of this magnitude would not go undetected in a GPS measurement and adjustment. An inaccurate value for any of the three coordinates results in relatively high residuals for the incorrect value(s) used in the adjustment process. The 1992 GPS network adjustment procedure indicated that the ellipsoidal surface, converted to latitudes, longitudes, and orthometric heights of control stations, was well defined by the given coordinates, which were referenced to NAD83 and NGVD29 (1978) datums.

The geologic setting of the 10 primary vertical-control stations are described in the following paragraphs. Aqueduct 100 (no. 162, fig. 10) is an iron-pipe bench mark along the First Los Angeles Aqueduct in the Sand Hills in western Antelope Valley. The Sand Hills anticline consists of coarse alluvial sand and gravel with a few exposures of medium- to coarse-grained sandstone (Dibblee, 1963, p. 200). This semiconsolidated, coarse-grained material is not susceptible to compaction and thus provides a stable setting for a primary vertical-control station. This bench mark was leveled to first-order standards of accuracy by the Los Angeles Department of Water and Power in 1907, in conjunction with the construction of the First Los Angeles Aqueduct, and later was adjusted to the NGVD29 datum. Although no subsequent leveling data are available for this bench mark to verify its relative stability, it was selected for control because of its presumed stability, its elevation had been measured to first-order standards of accuracy, and no other geodetic leveling has been done in this area where a primary vertical- control station was needed.

F1147 1961 (no. 170, fig. 10) is a U.S. Coast and Geodetic Survey (USC&GS) disk set in a boulder of tuff or tuffaceous sandstone of the Gem Hill formation (Dibblee, 1963, p. 175 and 187) 1.2 mi north of Rosamond. Because this bench mark is located on bedrock, it is considered an anchor bench mark and its 1965 elevation was used for the origin during 1972-73 leveling by NMD in northern Antelope Valley. The elevation from the 1978 SCRP leveling was held fixed for the 1992 GPS adjustment.

HPGN 0618 (no. 178, fig. 10), at the western end of Antelope Valley, is a horizontal-control station that also was used for vertical control. This station, on Interstate 5 near Gorman, is in mountainous terrain and thus is not susceptible to aquifer-system compaction. The elevation of HPGN 0618 was measured by first-order leveling in September 1992 (Larry Scott, Johnson-Frank & Associates, Inc., written commun., 1993) from nearby bench mark F54 1926. The elevation of bench mark F54 1926, determined from the 1978 SCRP leveling, was held fixed for the September 1992 leveling to HPGN 0618, which had been established in 1991.

Y1139 1961 (no. 216, fig. 10) is set in a quartz monzonite outcrop at the eastern extreme of Bissell Hills (fig. 1). Y1154 1961 (no. 217, fig. 10), although not set in an outcrop, is located where surficial quartz monzonite is mapped (Dibblee, 1963, pl. 9) at the southeastern extent of Rosamond Hills. The elevation histories for these bench marks are similar. The difference in elevation for the 1961-73 period was -0.129 and -0.127 ft, respectively, and the difference for the 1961-78 period was +0.079 and +0.091 ft, respectively. Leveling adjustments, different starting points, and tectonic activity probably contributed to the relatively minor changes in elevation. The 1978 SCRP elevations for both of these primary vertical-control stations were held fixed.

BM 336 (no. 19, fig. 10), also known as E489 1955, is a standard USC&GS disk set in a concrete post adjacent to Avenue M about 0.25 mi east of the crest of Quartz Hill (fig. 1), which is a small, locally prominent bedrock ridge. This bench mark was not included in the 1978 SCRP leveling; therefore, the elevation held fixed in the 1992 GPS

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adjustment was that determined in the 1991 LAC, DPW leveling. BM 2076 (no. 94, fig. 10) is a County Surveyor monument locating the ¼-corner between sections 28 and 33, T. 7 N., R. 14 W. This bench mark is about 0.55 mi east of BM 1327 (no. 79, fig. 7) east of Elizabeth Lake, which has been used twice since 1965 as a primary vertical-control station in LAC, DPW network surveys. Unfortunately, BM 1327 was not suitable for GPS surveys because it is under the canopy of a small tree and thus overhead visibility is poor. The elevations for BM 2076, a substitute for BM 1327, were determined by LAC in 1965 (twice), 1973, and 1991 (County of Los Angeles, 1981a, 1991). The maximum difference between values is 0.18 ft, indicating acceptable vertical stability; thus, BM 2076 was selected as a primary vertical-control station for the GPS network with its 1991 elevation held fixed.

BM 2706 (no. 129, fig. 10), also known as 115-4, is a County Surveyor monument on the west slope of Lovejoy Buttes (fig. 2). Since it was installed in 1961, elevations of this bench mark, determined in 1965, 1973, and 1981, indicate vertical stability. Therefore, this bench mark was selected to provide vertical control for the southeastern part of the subsidence monitoring network, and its 1981 elevation was used.

BM 5190 (no. 156, fig. 10), also known as GRINELL Reset 1929, is a horizontal-control station near the southeast corner of EAFB set in rock at the top of a hill composed of quartz monzonite (Dibblee, 1960, pl. 1). Because of its geologically stable foundation, the station was selected to be a primary vertical-control station also. The elevation of BM 5190 was determined by third-order leveling done by LAC, DPW, Road Department in May 1992 (table 4). A level line was run between County Surveyor monument BM 3454 (no. 140, fig. 7) at the intersection of Avenue E-8 and 200th Street East and County Surveyor monument BM 2393 (no. 120, fig. 7) at the intersection of Avenue G and 180th Street East. The elevations of these two bench marks (table 4), determined by leveling and adjustment in 1981, were held fixed, and the elevations of the inter- mediate bench marks were adjusted accordingly.

BM 5205 (no. 160, fig. 10), also known as M899 1955, is a standard USC&GS disk set just north of Vincent at the base of the San Gabriel Mountains south of Palmdale. The elevations of this bench mark were the same for the 1961, 1964, and 1965 first-order levelings. The difference of +0.25 ft between the first leveling (1955) and the most recent leveling (1978) is nearly within the ±0.2-ft measurement error range and indicates that this bench mark is acceptable as a primary vertical-control station for subsidence monitoring. The 1978 SCRP leveling elevation was held fixed in the 1992 adjustment.

Selection of Secondary Vertical-Control Stations

Secondary vertical-control stations for the land-subsidence monitoring network were selected at locations where updated elevations were needed in order to determine the current magnitude, rate, and areal distribution of subsidence. The locations of the secondary stations in Antelope Valley were determined on the basis of available information for the following categories: historical geodetic leveling, geology and subsurface lithology, ground-water pumpage or ground-water-level history, and projected ground-water use and land use.

On the basis of historical leveling, done predominantly by LAC, DPW, several areas had magnitudes of subsidence on the order of several feet for the period between the 1950's and 1981. The secondary vertical-control stations were selected in these areas to evaluate elevation changes since 1981. In contrast, some secondary stations were chosen because of the lack of leveling information in the area. About 15 bench marks whose elevations had never been determined or had been determined only by a GPS survey done a few years earlier (Blodgett and Williams, 1992) in the vicinity of EAFB were included in the network as secondary stations. Future monitoring would indicate if subsidence is occurring in these areas.

The composition of geologic materials that comprise the subsurface lithology at a given location is one factor that controls the potential for aquifer-system compaction and consequent land subsidence at that location. The presence of thin, fine-grained layers called interbeds and thick beds of fine-grained materials is indicative of a high potential for subsidence. Secondary vertical-control stations were located in areas that had been identified as having a relatively large percentage of fine-grained sediments (Durbin, 1978; Devin Galloway, USGS, oral commun., 1992).

Land subsidence in Antelope Valley is caused primarily by aquifer-system compaction induced by ground-water-level declines attributed to ground-water pumping. Therefore, the locations of former and current ground-water-pumping centers also were important in the selection of secondary vertical-control stations for the land-subsidence monitoring network. Because there are no oil or natural gas production wells in Antelope Valley, compaction resulting from these types of fluid withdrawals is not a concern in the study area.

Table 4. Leveled elevations of BM 5190 (GRINELL Reset 1929) and bench marks along Sierra Highway measured by Los Angeles County, Department of Public Works, 1992

[Elevations are referenced to NGVD29 and are measured to third-order standards of accuracy. OS, offset; RS, reset]

Map No.	Los Angeles County bench mark	Alternate name	Elevation	Map No.	Los Angeles County bench mark	Alternate	Elevation
120	BM 2393		[1]3,047.986	([4])	BM 4757		2,302.378
140	BM 3454		[1]3,070.036	([4])	BM 5202		2,301.057
156	BM 5190	[2]GRINELL RS1929	3,173.916	28	BM 479	[2]OBAN 1929 LINT	2,303.051
160	BM 5205	[2]M899 1955	3,084.921	([4])	BM 480		2,300.250
155	BM 5159	[2]B2657 1902	2,658.721	([4])	BM 2193		2,300.484
149	BM 4217	[2]W811 RS1973	2,577.054	29	BM 481	H487 1955	2,299.662
151	BM 4219	S12-19 1971	[3]2,529.351	([4])	BM 1440		2,300.857
([4])	BM 470		2,497.642	([4])	BM 1441		2,300.837
23	BM 471	[2]B57 RS1955	2,486.403	([4])	BM 1442		2,297.939
([4])	BM 2191		2,476.558	([4])	BM 1443		2,302.304
([4])	BM 4777		2,473.777	([4])	BM 1444		2,300.550
24	BM 472	T811 1947	2,447.086	([4])	BM 1445		2,301.711
([4])	BM 1427		2,442.428	([4])	BM 1446		2,300.119
([4])	BM 4774		2,421.931	30	BM 482	J487 1955	2,303.142
6	BM 118	S811 RS1955	2,396.472		BM 1447		2,303.778
([4])	BM 1429		2,395.792	([4])	BM 5203		2,301.394
([4])	BM 680		2,377.250	([4])	BM 1448		2,303.429
([4])	BM 2192		2,374.270	159	BM 5204	[2]N487 1955 OS 1989	2,304.823
([4])	BM 5194		2,374.193	([4])	BM 1450		2,303.018
([4])	BM 5195		2,354.066	31	BM 483	N487 1955	2,305.296
([4])	BM 5196		2,354.386	([4])	BM 1451		2,307.026
157	BM 5197	B2356 RS1961	2,349.505	([4])	BM 1452	2,307.098	
([4])	BM 5198		2,336.302	([4])	BM 1453	2,307.037	
([4])	BM 4779		2,336.334	32	BM 484	M487 1955	[3]2,307.772
25	BM 474	[2]B2335 1902	2,330.728	([4])	BM 101-152		2,309.126
([4])	BM 1430		2,324.462	([4])	BM 101-153		2,311.883
([4])	BM 1431		2,323.789	([4])	BM 101-154		2,312.816
158	BM 5199	Z56 RS1965	2,326.623	([4])	BM 101-155		2,313.777
([4])	BM 5200		2,323.538	([4])	BM 101-156	[2]U56 1926	2,326.067
([4])	BM 1433		2,323.672		BM KC1		2,340.840
([4])	BM 4455		2,316.888	([4])	BM KC2		2,368.580
26	BM 476	Z811 1947	2,316.226	([4])	BM 101-158		2,408.984
([4])	BM 5201		2,315.699	([4])	BM 101-158A		2,408.271
([4])	BM 1435		2,313.098	([4])	BM 101-159B		2,431.951
27	BM 477	Y56 1926	2,304.101	([4])	BM 101-159A		2,442.074
([4])	BM 4408		2,303.378	([4])	BM 101-159	[2]F1147 1961	2,447.564

[1]Elevation was held fixed from 1981 adjustment for leveling to BM 5190.
[2]Also measured by Global Positioning System (GPS) surveying in 1992.
[3]Elevation was held fixed from 1991 adjustment for Sierra Highway leveling.
[4]Bench mark was not used for this study.

If it is anticipated that ground-water pumping will begin at a new location, measurement of the land-surface elevation before the onset of pumping would be important. Likewise, if any change in local land use or ground-water use is anticipated, appropriately timed measurements would provide a comparison of relative subsidence rates between new and former land and ground-water uses. Changes in land use in Antelope Valley from partly fallow or active agricultural use to urban use have occurred during the last several decades (Templin and others, 1994). Although these changes have resulted in decreased ground-water pumpage, they have also significantly changed the spatial distribution of that pumpage. Agricultural pumping tends to be widespread, whereas pumping for urban use tends to concentrate around population centers. Locations of secondary vertical-control stations were densified in urban areas where differential magnitudes and rates of subsidence occurring within a relatively small area historically had been measured.

The configuration--location and spacing—of specific stations in the GPS network is a function of vector length and interstation geometry. Because systematic error in GPS surveying increases in direct proportion to vector length, limiting the distance between stations is desirable (Federal Geodetic Control Committee, 1989). For static geodetic surveys, 15 km often is cited as an ideal distance between stations, particularly for single-frequency observation. Most of the vectors in the 1992 Antelope Valley GPS survey were between 10 and 15 km. Vectors greater than 15 km were not uncommon because receivers were operated at six or seven stations simultaneously; thus, distances between the farthest points of a session were significantly greater. However, because many of these vectors were dependent (trivial) vectors, they were deweighted in postprocessing.

Ideal interstation geometry occurs when points are spaced at regular intervals in a geometric pattern. For Antelope Valley, the location of historical level lines generally dictated a rectilinear pattern. A higher density of secondary vertical-control stations near areas with the greatest measured land subsidence also was considered when designing the network configuration. Thus, many of the vector lengths are about 5 km because of the relatively close spacing of these stations. The number of receivers and time available to complete the survey is of practical, not theoretical, concern when considering the number of stations to include in the network. The combination of all the factors discussed above dictated the final design of the network configuration for monitoring land subsidence in Antelope Valley.

MEASUREMENT AND ADJUSTMENT OF GLOBAL POSITIONING SYSTEM NETWORK, 1992

Field Observations

The land-subsidence monitoring network was measured primarily between March 17 and May 8, 1992, using GPS instrumentation. The GPS surveying was done in the spring to minimize potential complications from inadvertently incorporating land subsidence caused by the onset and continuation of intensive ground-water pumping during the summer. It was necessary, however, to make additional observations on June 30 and between August 5-8, 1992, to provide requisite redundant observations that met accuracy standards and to observe bench marks previously inaccessible because of playa flooding. The duration of the observations ranged from 4.75 to 6.75 hours and was dependent on the amount of time predicted for ideal satellite configurations. Satellite transmissions were recorded every 15 seconds when the satellites were at least 10 degrees above the horizon.

The GPS equipment consisted primarily of Ashtech dual-frequency receivers (LD-XII and MD-XII) with micro-strip antennas. Four Trimble dual-frequency receivers (4000 SST) also were operated between May 4-8, 1992. These data were converted to Receiver Independent Exchange (RINEX) format and then to Ashtech format prior to postprocessing. An optical plummet mounted on a tripod enabled the antenna to be mounted in the center of and plumb to the setup mark etched in the bench-mark monument. All antennas were mounted with the phase center oriented north. Between three and seven units operated simultaneously in the static mode, with four receivers in operation for nearly half (15) of the 35 days of observation. Data were unusable for only one receiver for 1 day of observations because of sporadic equipment malfunctions. Of the 85 stations in the network, 33 percent (28) were occupied once, 51 percent (43) were occupied twice, and 16 percent (14) were occupied between three and five times.

Vector Computation

The two primary stages in the postprocessing of differential GPS geodetic surveying data are vector computation and network adjustment. In the first phase of postprocessing, computations result in vectors defined by d*x*, d*y*, and d*z* values in a Cartesian coordinate system for differences in three-dimensional location between two stations observed simultaneously. In the second phase, network adjustment converts Cartesian coordinates into values of the local horizontal and vertical coordinate systems. The horizontal datum used for the subsidence-monitoring network was NAD83, and NGVD29 was the vertical datum used, which allowed comparison of GPS-derived elevations with historical elevations.

Data were processed using Ashtech software called GPPS, version 4.5. When computing a vector between two stations, a differencing technique was used to minimize most satellite-, station-, and observation-dependent errors. For example, a double-difference measurement is a difference in measurements between two receivers recording signals from two satellites at the same time. The primary purpose of double-difference processing is to correctly determine the integer number (interchangeably termed "ambiguity" or "bias") of carrier-phase cycles of either frequency between the satellite and receiver. Signals from the satellites are radio waves transmitted at L1 frequency (1.57542 MHz) and at L2 frequency (1.22760 MHz). Dual-frequency processing enables a time correction to be calculated for signal attenuation (time delay) of radio signals traveling different distances through the ionosphere. Signals received from satellites less than 20 degrees above the horizon were masked (not included) in the processing. Broadcast (predicted), rather than precise, ephemerides (satellite orbits) were used in vector computations. Because most of the vector lengths between stations were relatively short (less than 20 km) and the duration of observations was very long, the reduction in error from the use of precise ephemerides probably would have been insignificant.

All satellite observations were processed in two ways to obtain both single- and dual-frequency solutions and some data, particularly those with long vector lengths, were processed a third way. Single-frequency processing results in bias-fixed, double-difference solutions generated for L1-frequency data and is not corrected for ionospheric effects. Dual-frequency processing usually results in bias-fixed, ionosphere-corrected, double-difference solutions. If bias-fixing for dual-frequency processing is not successful, the bias for one or more satellites may be fixed to the wrong integer. If partial-fixing occurred during dual-frequency processing, which commonly happened for data with long vector lengths, the data were reprocessed a third time. In these cases, solutions were generated such that the bias was not forced to be an integer; instead, processing was complete when a real number had been computed. These solutions are called bias-float, ionosphere-corrected, double-difference solutions.

Results from each type of processing were examined to select the vector solution with the lowest RMSE for inclusion in the input data set for network adjustment. Single-frequency processing produced better results for most vectors than did dual-frequency processing because the average length of all 332 vectors generated was less than 12 km (table 5). Single-frequency processing, which does not include an ionospheric correction, is acceptable for relatively short vectors (less than 15 km) because signals transmitted by the satellites to stations in close proximity are assumed to be traveling at virtually the same angle and, thus, through a similar distance of ionosphere. For 10 vectors ranging in length from 23 to 60 km (table 5), dual-frequency, bias-float processing produced the best results. These vectors were relatively long and the correct integer number of the biases could not be solved with sufficient certainty. Dual-frequency, bias-fixed processing produced the best results for the remainder of the vectors (68), which had an average length of about 18 km (table 5).

Minimal- and Multiple-Constraint Network Adjustments

After the appropriate mode of processing was selected for each vector, a minimal-constraint adjustment was run to determine the quality of each vector relative to the other vectors without concern about fitting the network to local horizontal or vertical control. In a minimal-constraint adjustment, two horizontal coordinates and one vertical coordinate are supplied as known values. For the Antelope Valley GPS survey, the NAD83 coordinates of horizontal-control station OBAN 1929 LINT were held fixed and the NGVD29 (1978 adjustment) elevation for F1147 1961 was held fixed in the minimal-constraint adjustment. The ellipsoidal height for F1147 1961, 714.252 m (2,343.462 ft), was computed by subtracting the GEOID90 geoidal separation value of -31.734 m (104.119 ft) from the published elevation of 745.986 m (2447.581 ft). The output for the minimal-constraint adjustment was checked for misclosure to detect any field or office blunders (nonsystematic errors) and poor quality vectors. Vectors that required a large adjustment (high residual) relative to the statistically normal adjustment allowed for the vector length—those that had a high standardized residual—were reexamined. Large adjustments indicate the potential for uncorrected blunders in a data set. Examples of blunders include an incorrect bench-mark name or wrong height of instrument (H.I.) measured or recorded in the field or entered in the computer file.

After checking for and correcting blunders, the minimal-constraint adjustment was rerun so that the quality of the method of measurement (GPS observation) could be quantified. Assignment of appropriate a priori weights to error estimates in the x, y, and z coordinates resulted in a value close to unity for the Standard Error of Unit Weight (SEUW), which is the desired goal. For the Antelope Valley network, the appropriate minimal-constraint a priori errors for bias-fixed vector solutions were ±(3 mm + 0.4 ppm) for x, ±(4 mm + 0.4 ppm) for y, and ±(5 mm + 0.5 ppm) for z, and twice each of those for bias-float solutions. These low error values indicate that the quality of the GPS-survey measurements is high.

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Table 5. Antelope Valley Global Positioning System-network vectors by processing type for the 1992 GPS survey

[Bench mark Global Positioning System code name identified in table 2. km, kilometer; m, meter; 1σ, 1 standard error; --, no data]

1992 Julian day	Vector			1992 Julian day	Vector		
	Name	Length (km)	1σ (m)		Name	Length (km)	1σ (m)
Single-frequency, bias-fixed processing							
078	OBAN-ON48	5.74	0.006	094	MDC6-TRN8	6.70	0.006
	ON48-_U56	6.12	.006		MDC4-MD30	7.12	.005
	OBAN-_U56	11.9	.005		MDC6-MD30	7.43	.006
					GRNL-TRN8	9.25	.005
079	147F-_U56	2.31	.005		GRNL-MD30	11.5	.005
	_U56-ALDR	4.67	.005				
	147F-ALDR	5.45	.004	095	139Y-SFT1	5.09	.004
					OC68-RLB5	5.35	.005
080	6116-O122	4.94	.005		JUNC-139Y	5.67	.004
	RLB5-SFT1	8.06	.005		RLB5-139Y	5.96	.004
					RLB5-JUNC	6.31	.005
081	OBAN-154F	3.19	.005		OC68-JUNC	8.97	.006
	154F-488Z	5.85	.005		JUNC-SFT1	10.6	.005
	OBAN-488Z	6.53	.005		OC68-139Y	11.0	.005
	154F-6130	6.55	.005		OC68-SFT1	13.3	.006
	488Z-6130	7.66	.005				
	OBAN-6130	9.65	.005	096	O55H-STP1	3.52	.004
					155P-O55H	4.21	.005
083	7ASK-GWM2	2.55	.005		6116-155P	4.79	.005
	154Y-155D	4.53	.005		155P-STP1	6.34	.005
	GWM2-155D	4.65	.005		6116-O55H	8.99	.005
	7ASK-155D	5.03	.004		6116-STP1	10.8	.005
	154Y-7ASK	8.93	.004				
	154Y-GWM2	9.13	.005	097	7ASK-O55H	3.13	.005
					7ASK-STP1	3.45	.005
084	139T-139Y	3.07	.005		O55H-STP1	3.52	.004
	139T-GWM2	4.87	.006		STP1-TRN8	4.87	.005
	JUNC-139Y	5.67	.004		RLB3-TRN8	5.91	.005
	139Y-GWM2	7.61	.005		STP1-RLB3	6.09	.005
	JUNC-139T	8.03	.006		7ASK-RLB3	7.15	.005
					O55H-TRN8	8.10	.005
085	6130-O122	6.45	.005		7ASK-TRN8	8.15	.005
					O55H-RLB3	9.23	.005
092	155D-GWM4	2.38	.004				
	GWM4-7ASK	3.75	.004	098	BKHN-155V	3.47	.005
	155D-7ASK	5.03	.004		BKHN-GWM4	4.95	.005
					155V-O122	5.14	.005
093	MD33-RLB6	2.38	.006		155V-GWM4	7.22	.005
	MD30-MD33	4.61	.006		BKHN-O122	8.60	.005
	O38R-OC68	5.73	.006				
	RLB6-O38R	6.18	.006	099	155P-155M	3.45	.005
	MD30-RLB6	8.87	.006		155M-MDC4	4.25	.005
	[1]MD30-O38R	15.0	.008		155V-155P	6.61	.005
					155P-MDC4	7.65	.005
094	TRN8-MD30	2.83	.005				
	MDC4-TRN8	4.61	.005	100	LS38-154F	3.65	.005
	GRNL-MDC4	4.76	.004		ALDR-LS38	8.06	.005
	MDC6-MDC4	5.26	.005		ALDR-154Y	9.28	.004
	GRNL-MDC6	6.24	.005		154F-ALDR	11.2	.005

Table 5. Antelope Valley Global Positioning System-network vectors by processing type for the 1992 GPS survey--*Continued*

1992 Julian day	Vector			1992 Julian day	Vector		
	Name	Length (km)	1σ (m)		Name	Length (km)	1σ (m)
			Single-frequency, bias-fixed processing--*Continued*				
100	154Y-LS38	11.4	0.004	120	2706-2716	6.24	0.007
	154Y-154F	14.9	.005		306E-2657	6.54	.007
					2716-306E	10.3	.007
113	2746-2706	6.66	.007		2706-306E	16.2	.007
	2746-PEAR	9.03	.007		2716-2657	16.8	.077
	0705-2746	9.08	.007		[1]2706-2657	22.7	.006
	2706-PEAR	11.1	.005				
	[2]PEAR-489E	28.1	--	126	3738-2180	2.60	.006
					488Z-2335	3.76	.005
114	LS46-GRNL	8.40	.007		2169-1171	4.14	.006
	PEAR-2706	11.1	.005		2180-488Z	4.36	.006
	LS46-MOND	11.2	.008		2169-2037	4.92	.006
	2706-LS46	11.3	.008		3738-488Z	5.41	.006
					3738-1171	6.53	.006
115	O122-1171	4.09	.005		2180-1171	7.79	.006
	LS53-1171	7.19	.007		2180-2335	8.03	.006
	GRNL-LS53	7.56	.006		2180-2169	8.33	.006
	LS53-O122	8.04	.006		3738-2169	8.36	.006
	GRNL-MOND	10.7	.006		2037-1171	9.02	.006
	GRNL-O122	13.9	.004		3738-2335	9.13	.006
	GRNL-1171	14.4	.006		2180-2037	10.5	.006
	LS53-MOND	17.0	.008		3738-2037	11.6	.006
	1171-MOND	24.2	.007		1171-488Z	11.8	.005
	[1]1171-PEAR	24.2	.007		2169-488Z	12.7	.006
	O122-MOND	24.4	.007		2037-488Z	14.6	.006
	[1]O122-PEAR	28.3	.007		1171-2335	15.6	.006
					2169-2335	16.3	.006
116	PEAR-306H	4.03	.006		2037-2335	17.6	.006
	2616-899M	6.97	.006				
	306H-2616	7.89	.007	127	_B57-811W	3.44	.006
	PEAR-2616	11.9	.007		811W-PARP	3.72	.005
	306H-899M	12.9	.007		_B57-489E	4.94	.006
	PEAR-899M	16.8	.006		_B57-PARP	5.14	.006
					OBAN-2335	5.26	.005
117	811W-1380	3.07	.005		2335-_B57	5.64	.006
	811W-2657	5.27	.005		811W-489E	5.67	.005
	1380-2657	5.57	.005		OBAN-AVEN	7.22	.005
	899M-2657	7.07	.006		2335-489E	7.93	.005
	1380-899M	12.1	.006		2335-811W	9.08	.005
	811W-899M	12.3	.006		PARP-489E	9.12	.006
					2335-PARP	9.91	.006
118	1494-1483	7.39	.006		2335-AVEN	10.8	.006
	973X-1494	7.60	.005		OBAN-_B57	10.9	.006
	973X-O618	10.7	.006		OBAN-489E	12.5	.006
	973X-1483	15.0	.007				
	1494-O618	17.6	.007	128	489E-1380	3.96	.005
					306B-_537	4.84	.007
119	2030-2037	5.73	.006		_537-489E	6.99	.006
	2030-PARP	5.92	.006		_537-AVEN	8.09	.006

Table 5. Antelope Valley Global Positioning System-network vectors by processing type for the 1992 GPS survey--*Continued*

1992 Julian day	Vector			1992 Julian day	Vector		
	Name	Length (km)	1σ (m)		Name	Length (km)	1σ (m)
			Single-frequency, bias-fixed processing--*Continued*				
128	306B-AVEN	8.97	0.006	130	[1]3549-1483	18.9	0.012
	3636-AVEN	9.66	.005		[1]BULL-2076	24.4	.013
	3636-306B	9.80	.007		[1]A100-2076	24.6	.010
	306B-2076	10.8	.008		[1]1483-2076	25.3	.013
	_537-1380	10.9	.007				
	3636-_537	13.2	.007	183	973X-1494	7.60	.005
	3636-2076	13.5	.008		0618-973X	10.7	.006
	_537-2076	15.3	.008		0618-1494	17.6	.007
	AVEN-2076	18.8	.007		973X-BULL	20.3	.008
	[1]3636-489E	19.5	.007		0618-BULL	28.8	.008
	[1]3636-1380	23.5	.007				
				218	LS38-ROL1	2.84	.005
129	146V-2235	3.98	.006		BKHN-154Y	3.39	.004
	AVEN-2235	5.06	.006		ROL1-BKHN	9.02	.005
	147F-146V	5.71	.006		ROL1-154Y	9.16	.004
	2317-3636	5.86	.007		LS38-BKHN	10.5	.005
	146V-2317	7.39	.007		LS38-154Y	11.4	.004
	147F-2235	7.43	.006				
	AVEN-2317	8.01	.006	219	155M-RLB4	2.29	.006
	2235-2317	8.02	.007		RLB3-RLB1	4.68	.006
	146V-AVEN	8.44	.006		155M-GRNL	7.34	.005
	AVEN-3636	9.66	.005		RLB4-GRNL	7.43	.006
	2235-3636	12.3	.007		RLB3-RLB4	8.63	.006
	147F-AVEN	12.5	.005				
	146V-3636	12.9	.007	220	RLB1-SFT1	2.63	.005
	147F-2317	13.1	.007		RLB1-139Y	4.99	.005
	3636-A100	17.7	.009		SFT1-139Y	5.09	.004
	147F-3636	18.6	.006		RLB1-RLB6	5.55	.005
	2317-A100	18.9	.010		RLB5-RLB1	5.79	.005
					RLB5-139Y	5.96	.004
130	BULL-1483	6.74	.007		SFT1-RLB6	7.56	.005
	[2]A100-BULL	7.05	--		RLB5-RLB6	7.64	.005
	[1]BULL-1276	7.32	.007		RLB5-SFT1	8.06	.005
	[1]1483-1276	8.58	.008		139Y-RLB6	10.2	.005
	1290-2076	8.86	.010				
	3549-A100	8.93	.010	221	ROL1-3631	0.632	.005
	1290-1276	9.79	.010		154U-ALDR	3.18	.005
	3549-1290	9.87	.010		ALDR-3631	4.91	.005
	[1]A100-1276	10.8	.012		154U-3631	5.15	.006
	[1]3549-1276	11.8	.011		154U-ROL1	5.46	.005
	[1]3549-BULL	13.5	.012		ALDR-ROL1	5.48	.005
	[1]A100-1483	13.8	.013		154Y-154U	6.10	.005
	[1]A100-1290	15.8	.011		154Y-ALDR	9.28	.004
	[1]BULL-1290	16.1	.011				
	[1]2076-1276	17.4	.012		Average vector length		9.14
	[1]3549-2076	18.0	.011		Minimum vector length		0.632
	[1]1483-1290	18.3	.011		Maximum vector length		28.8

Footnotes at end of table.

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Table 5. Antelope Valley Global Positioning System-network vectors by processing type for the 1992 GPS survey--*Continued*

1992 Julian day	Vector Name	Vector Length (km)	Vector 1σ (m)	1992 Julian day	Vector Name	Vector Length (km)	Vector 1σ (m)
Dual-frequency, bias-fixed processing							
080	GRNL-6116	8.94	0.005	118	0618-1483	24.7	0.008
	GRNL-O122	13.9	.004				
				119	2037-2706	9.51	.006
082	139Y-147F	26.4	.007		PARP-2037	11.5	.006
					2030-2706	14.7	.007
084	JUNC-GWM2	12.9	.006		PARP-2706	19.8	.006
				127	811W-OBAN	14.3	.006
085	154Y-6130	11.9	.005		PARP-OBAN	14.9	.006
	154Y-O122	12.0	.004		AVEN-489E	14.9	.005
	147F-154Y	14.5	.005		_B57-AVEN	15.7	.006
	147F-6130	17.4	.006		811W-AVEN	18.9	.006
	147F-O122	22.2	.005		AVEN-PARP	20.5	.006
093	MD33-O38R	10.5	.007	128	489E-306B	9.86	.007
	OC68-RLB6	10.6	.005		1380-306B	13.7	.007
	MD33-OC68	14.7	.007		AVEN-489E	14.9	.005
	[1]OC68-MD30	18.8	.007		489E-2076	17.2	.008
					AVEN-1380	18.7	.006
098	GWM4-O122	11.5	.005		1380-2076	20.0	.008
099	155V-155M	10.0	.005	129	146V-A100	24.9	.010
	155V-MDC4	14.3	.005		A100-AVEN	26.4	.009
					A100-2235	26.8	.010
113	0705-PEAR	14.6	.007		147F-A100	29.8	.010
	0705-2706	15.6	.006				
	899M-489E	16.0	.006	183	1276-BULL	7.32	.007
	PEAR-899M	16.8	.006		BULL-1494	13.2	.007
	2706-899M	23.5	.006		1276-1494	15.9	.008
					1276-973X	23.5	.008
114	GRNL-MOND	10.7	.006		0618-1276	33.2	.009
	0705-PEAR	14.6	.007				
	2706-0705	15.6	.006	219	RLB3-155M	10.5	.005
	2706-GRNL	18.8	.006		RLB1-RLB4	13.2	.007
	2706-MOND	21.8	.007		RLB1-155M	14.9	.006
	LS46-PEAR	22.4	.008		RLB3-GRNL	15.1	.005
	0705-LS46	22.4	.009		RLB1-GRNL	19.8	.006
	0705-MOND	28.3	.009				
	GRNL-PEAR	29.8	.007	221	154Y-ROL1	9.16	.004
	0705-GRNL	30.8	.008		154Y-3631	9.27	.005
	PEAR-MOND	32.4	.008				
					Average vector length	17.9	
115	PEAR-LS53	24.7	.008		Minimum vector length	7.32	
	PEAR-GRNL	29.8	.007		Maximum vector length	33.2	
	PEAR-MOND	32.4	.008				

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Table 5. Antelope Valley Global Positioning System-network vectors by processing type for the 1992 GPS survey--*Continued*

1992 Julian day	Vector			1992 Julian day	Vector		
	Name	Length (km)	1σ (m)		Name	Length (km)	1σ (m)
Dual-frequency, bias-float processing							
082	[1]GRNL-139Y	22.8	0.006	113	[2]2746-899M	25.1	--
	[1]0805-139Y	33.9	.034		[2]2706-489E	28.9	--
	[1]GRNL-147F	34.3	.006		[2]0705-899M	31.4	--
	[1]GRNL-0805	37.6	.034		[2]2746-489E	33.5	--
	[1]0805-147F	60.0	.035		[2]0705-489E	41.9	--
		Average vector length			34.9		
		Minimum vector length			22.8		
		Maximun vector length			60.0		

[1]Bias-float solution used in adjustment.
[2]Vector excluded from final multiple-constraint adjustment.

For example, the allowable misclosure with these errors for a bias-fixed vector of 10 km is ±7 mm in the *x* coordinate, ±8 mm for *y*, and ±10 mm for *z*.

The second step in network adjustment procedures is a multiple-constraint adjustment in which the coordinates of the proposed horizontal and vertical control are held fixed. High standardized residuals in the output may indicate that the quality of the coordinates of one or more control stations is questionable. After control issues were resolved, a multiple-constraint adjustment was done with the same a priori errors that had been assigned for the minimal-constraint adjustment and resulted in a relatively low SEUW of 1.521. This low value indicates that incorporation of the local datum reference systems, including estimated geoidal-separation values, did not introduce much error related either to the original measurement of coordinates by conventional methods or to intrasurvey movement of control stations. High values of SEUW are an indicator that (1) the specified control values may not have been measured originally to the same datum, (2) those measurements had low standards of accuracy, or (3) crustal movement (vertical or horizontal or both) may have occurred between measurements.

The multiple-constraint adjustment output was reexamined for high standardized residuals. To eliminate high values, the importance (weight) of those vectors is reduced by increasing the allowable error or adjustment. The bias-float solution, with a priori errors twice those of a bias-fixed solution, allows more of an adjustment to be made to the vector's coordinates without influencing other vectors. Starting with the vector with the highest statistical errors, the bias-float solution was selected for one vector at a time and an adjustment was rerun. If that vector's standardized residual was not reduced to an acceptable level, it was excluded from the data set and the network was readjusted. Of the 332 vectors in the Antelope Valley GPS network, 7 vectors were excluded from the multiple-constraint adjustment and 27 were selected as bias-float vector solutions (table 5).

The final step in the multiple-constraint adjustment was to assign values to the a priori errors that reflected the quality of the adjusted network relative to the local datum coordinate systems. Appropriate values for a priori errors have been selected when the resulting SEUW value equals or approaches 1 (unity) and if the magnitude of the errors are reasonable for the type of GPS survey done. A SEUW of 1.003 resulted when the a priori errors for bias-fixed vector solutions were ±(6 mm + 0.6 ppm) for *x*, ±(7 mm + 0.6 ppm) for *y*, and ±(8 mm + 0.6 ppm) for *z*. The corresponding a prior errors for biasfloat vector solutions were ±(13 mm + 1.2 ppm) for *x*, and ±(15 mm + 1.2 ppm) for *y* and *z* coordinates.

The 95-percent confidence (2σ) level of accuracy for GPS-derived orthometric heights of the multiple-constraint adjustment ranged from ±0.010 m (0.032 ft) to ±0.024 m (0.078 ft), except for bench mark HPGN 0805 (no. 180, fig 10). Because this bench mark was so distant from most of the network and because it was outside the area bounded by the control, its 2σ value of ±0.084 m (0.276 ft) was nearly an order of magnitude higher. Except for HPGN 0805 and the 10 vertical-control stations (for which no new elevations or standard errors were computed), the average 2σ standard error was ±0.015 m (0.050 ft) for the 74 GPS-derived elevations (table 2).

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Accuracy and Limitations of Geodetic Global Positioning System-Derived Orthometric Heights

Geodetic quality measurement of *x*, *y*, and *z* coordinates is best accomplished using relative-positioning techniques. The geometric classification of accuracy for relative-positioning determinations is based on the internal consistency of the GPS network (Federal Geodetic Control Committee, 1989), which is characterized during a minimal-constraint adjustment. Accuracy standards are based on the assumption that errors can be assumed to follow a normal distribution. Such a distribution applies only to independent, random errors and assumes that systematic errors and blunders have been eliminated or reduced sufficiently to permit treatment as random errors. Major factors affecting the accuracy of relative-positioning determinations in static GPS geodetic surveying mode are (1) accuracy of satellite positions (ephemerides), (2) accuracy of modeled atmospheric refraction, (3) receiver-timing bias, and (4) blunders. Selective availability (SA) and satellite code encryptation restrictions have no effect on static relative-positioning techniques. However, locally severe storm fronts and solar activity could substantially degrade signal quality (Federal Geodetic Control Committee, 1989).

Ellipsoidal heights are converted to orthometric heights when the multiple-constraint adjustment calculations include geoidal separations. Accuracies of GPS-derived orthometric heights are a function of the accuracies for ellipsoidal heights, elevations of vertical-control stations, and estimates of geoidal separations. For high quality (low error) GPS surveys, such as the survey done in Antelope Valley, errors in calculating orthometric heights result primarily from inaccuracies associated with modeled geoidal-separation values.

Accuracy of vertical-control station elevations was qualitatively assessed by comparing the output statistics of the multiple-constraint adjustment prior to and after holding fixed the elevation of one vertical-control station at a time. Relatively low values of standardized residuals and of the SEUW indicated high quality vertical control.

Selection of the better geopotential model for this study area was achieved by comparing the geoidal separations calculated by the GEOID90 and GEOID93 models to differences in elevations determined by spirit leveling for seven pairs of bench marks along Sierra Highway (table 6). The leveling was done within 1 month of the GPS observations so that subsidence, or real changes in the vertical coordinate, would not be a factor in the comparison. Given that the differences in elevations determined using differential leveling represent true values, the geoidal separations derived from the GEOID93 model resulted in elevation differences that were, on average, a few hundredths of a foot (millimeters) less accurate than those obtained using the GEOID90 model. The differences between the two modeled sets, which ranged from 0.004 to 0.039 ft (1 to 11 mm), were virtually insignificant, but the GEOID93 model was not used because, overall, it did not improve the geoid estimates for the examined area.

Table 6. Comparison of elevation differences computed using geopotential models GEOID90 and GEOID93 and determined by differential leveling for several bench-mark pairs along Sierra Highway between Palmdale and Rosamond, Antelope Valley

[ft, foot; mi, mile]

Bench-mark pair	Distance between bench marks (mi)	Elevation difference (ft)			Difference between leveled/ GEOID90 differences (ft)	Difference between leveled/ GEOID93 differences (ft)
		Differential leveling (1992)	GPS, using GEOID90	GPS, using GEOID93		
BM 5159 - BM 4217	3.3	81.667	81.742	81.753	0.075	0.086
BM 4217 - BM 471	1.9	90.651	90.743	90.733	.092	.082
BM 471 - BM 474	3.3	155.675	155.664	155.684	-.011	.009
BM 474 - BM 479	3.4	27.677	27.724	27.721	.047	.043
BM 479 - BM 5204	3.4	-1.772	-1.837	-1.850	-.065	-.078
BM 5204 - U56	4.0	-21.244	-21.304	-21.343	-.060	-.099
U56 - F1147	.1	-121.497	-121.554	-121.581	-.057	-.084
BM 5159 - BM 479	11.9	355.670	355.873	355.890	.203	.220
BM479 - F1147	7.5	-144.513	-144.695	-144.774	-.182	-.261

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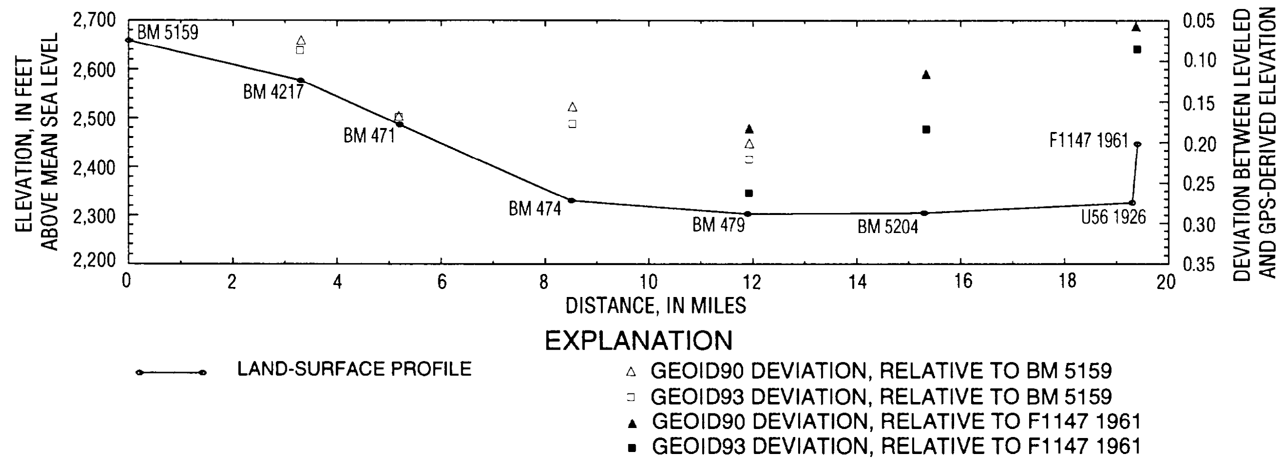

Figure 11. Land-surface profile on Sierra Highway between Palmdale and Rosamond and error for Global Positioning System-derived elevation differences relative to leveled differences of bench-mark pairs.

Table 7. Comparison of elevations for 11 bench marks in Antelope Valley determined by differential leveling and by a Global Positioning System (GPS) multiple-constraint adjustment

[Elevations are referenced to NGVD29. ft, foot]

Bench-mark name	Differential leveling elevations (ft)		1992 GPS elevation (ft)	Difference betweem methods (ft)
	1991	1992		
BM 135	2,935.912		2,936.066	-0.154
BM 171	2,615.072		2,615.063	.009
BM 471		2,486.403	2,486.274	.129
BM 474		2,330.728	2,330.610	.118
BM 479		2,303.051	2,302.886	.165
BM 1380	2,640.107		2,640.123	-.016
BM 2030	2,486.904		2,486.914	-.010
BM 2616	2,705.548		2,705.720	-.172
BM 4217	2,577.054		2,577.017	.037
BM 5159		2,658.721	2,658.759	-.038
BM 5204		2,304.823	2,304.723	.100
	Average deviation		$\frac{\Sigma\|x\|}{n}$	= 0.086

The ability of GEOID90 to correctly estimate geoidal separations was evaluated in two ways. A comparison was made between elevations determined by conventional differential leveling that was done in either 1991 or 1992 and orthometric elevations calculated using GPS methods (table 7). For 11 bench marks, the average absolute value of the elevation differences between the two methods of measurement was 0.086 ft (0.026 m). The greatest inaccuracy of modeled geoidal separations would be expected to coincide with the lowest elevation of a valley's land-surface profile, which is the gravity low as well, because of inaccuracy in defining the geoid. For the profile along Sierra Highway, differences in elevation between the two topographically highest and six lower bench marks were calculated from elevations determined by leveling and by using modeled geoidal separations applied to ellipsoidal heights to ascertain the deviations from the leveled differences (fig. 11). Calculations were made relative to BM 5159 and F1147 1961, the highest bench marks on opposite ends of the profile. The largest deviations do occur at the lowest elevations along the profile. These calculations yielded a maximum geoidal-separation component of error associated with orthometric elevations computed by the GEOID90 model of about 0.2 ft (0.06 m) for this part of Antelope Valley (fig. 11). Deviations in elevation of about 0.1 to 0.2 ft for bench marks at this spacing (maximum of 12 mi) are consistent with the 0.3-ft error related to geoid estimations computed for the longer dimension (60 mi) of the valley.

When monitoring the change in vertical position of a station over time, neither local reference systems nor geoidal-separation estimates need to be incorporated into the height component. The accuracy of changes in vertical position then depends only on the accuracy of ellipsoidal-height determinations. Furthermore, because vectors are the first product of GPS postprocessing and thus have somewhat less error than coordinates determined for individual bench marks, changes in ellipsoidal-height differences for a vector rather than changes in ellipsoidal heights for a bench mark are often examined in monitoring programs. For the minimal-constraint adjustment of the 1992 GPS survey, the 1σ error of the vertical component of the vectors usually was between ±0.004 m (0.013 ft) and ±0.008 m (0.026 ft) (table 5). The magnitude of these errors, or some multiple thereof, could be used to determine the timing of repeat surveys for monitoring land subsidence.

PWS-0195-0047

DETERMINATION OF LAND SUBSIDENCE, ABOUT 1930-92

Magnitude and Distribution of Subsidence

Land subsidence was determined by examining elevation data for 218 bench marks (table 8): 160 bench marks have a LAC designation and 58 bench marks were either measured or recently installed by other agencies. If elevation data were available for the early period (about 1930-60), subsidence for the entire period (about 1930-92) is considered "calculated;" if subsidence for the first part of this period was determined by interpolating from a previously published subsidence-rate contour map (Mankey, 1963), it is considered "estimated." The maximum magnitude of calculated land subsidence between about 1926 and 1992 was 6.0 ft at BM 474 (no. 25, fig. 8) near Avenue I and Sierra Highway in Area 2 (fig. 1). Less than 0.5 mi east, at Avenue I and Division Street, 6.6 ft of subsidence--the largest magnitude of either calculated or estimated land subsidence in Antelope Valley--was estimated at BM 53 (no. 1, fig. 8) for about 1930-81. Subsidence of 6.0 ft was similarly estimated for about 1930-81 at BM 666 (no. 41, fig. 8), also at Avenue I and Sierra Highway. Several additional bench marks that are within 1.5 mi east and west of Sierra Highway and within 0.5 mi north and south of Avenue I have magnitudes of estimated subsidence ranging between 4.5 and 6.0 ft since about 1930.

Two other locations in Antelope Valley also have estimated amounts of subsidence of more than 5 ft. At BM 1171A (no. 69, fig. 8) near Avenue G-8 and 90th Street East in Area 3 (fig. 1), subsidence of 6.4 ft was estimated for 1930-92. Subsidence of 5.2 ft was estimated for BM 2180 (no. 99, fig. 8) at Avenue I and 45th Street East in Area 4 (fig. 1) for the same period. In Area 1 between Avenues F and J and 40th Street West to 90th Street West (fig. 1), the estimated magnitude of subsidence for 1930-92 was between 2 and 3 ft. This area is identified because, in contrast to the timing of subsidence in the other areas, most of the subsidence in Area 1 occurred before 1960.

Subsidence estimates for the early period were based on a contour map prepared by Mankey (1963), which showed contours of equal mathematically averaged rates of subsidence. The rate of subsidence for a selected bench mark was determined by interpolating between contour lines to the nearest 0.001 ft/yr and then was multiplied by 30 years (usually) to obtain the magnitude of subsidence for the early period. The number of years used in the calculation was the same as the number of years in the period of record for the historically leveled bench mark nearest the selected bench mark. Estimates were used if they met the following criteria: (1) contours were not affected by the apparent error for bench mark US827 at Sierra Highway and Avenue P, (2) contours were based on 20 to 30 years or more of leveling data, and (3) bench marks of interest were within 1 mi of a leveled bench mark for which the rate of subsidence had been calculated and contours subsequently drawn. Exceptions were made for four bench marks [BM 1159, BM 1165B, BM 1171A, and BM 2180 (map nos. 65, 67, 69, and 99, respectively, fig. 8)] when the third criterion was not met. Subsidence estimates for the early period for these four bench marks, all measured in 1992 using GPS, ranged from about 0.8 to 1.4 ft (table 8) and represented only 15 to 32 percent of the total subsidence calculated for the entire period (1930-92).

Magnitudes of calculated and estimated subsidence as of 1992 for 218 bench marks are listed in table 8 and presented as a contour map in figure 8 with different symbols used to represent various periods of measurement. In table 8, an "e" precedes the capital-letter code listed if subsidence was estimated for the first period. Estimates for the first period were made if the elevation of a bench mark was last determined in 1981, 1991, or 1992 and the three criteria previously listed were met. Of the 55 bench marks that met all these criteria, the earliest leveling generally had been done between 1955 and 1962. When a bench mark was leveled about the midpoint of the 1930-92 period, the change in elevation for the entire period of record was calculated by subtracting the most recent measurement from the earliest measurement thus avoiding the cumulative incorporation of measurement error. Most of the measurements for the 218 bench marks were made in the second period (about 1957-92); bench marks with measurements from the earlier period can be identified by the code "A" that is not preceded by an "e."

A letter code, A-E, was assigned to each bench mark to represent the period of record for which subsidence calculations were made. The letters also correspond to the five symbols used in figure 8 that represent the periods of record used to determine the cumulative magnitude of subsidence. The letter "A" represents the longest time period and corresponds to the five-point star symbol in figure 8. There are 18 bench marks in the data set that have a leveling history starting within about 5 years of 1930. These bench marks were originally leveled between 1926 (adjusted to NGVD29) and 1937.

Table 8. Calculated and estimated subsidence from about 1930 to 1992 for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties

[Codes represent periods of leveling: A, between 1926-40 and 1988-92; B, between 1929, 1930, or 1940 and 1981; C, between 1952-61 and 1991 or 1992; D, between 1955-57 and 1981; E, for all other periods. Code letters correspond to symbols in figure 5 as follows: A, five-point star; B, square; C, triangle; D, asterisk; E, plus. EAFB, Edwards Air Force Base. e, estimated; ft, foot; --, no data]

Map No.	Subsidence (ft)		Period of record, second period	Total subsidence, calculated or estimated (ft)	Period of record available	Code	Nearest cross streets or township/range location
	Estimated, first period	Calculated, second period					
1	1.80	4.78	1955-81	6.6	1930-81	e B	Avenue I and Division Street
2	1.86	2.99	1962-81	4.8	1930-81	e B	Avenue I and 5th Street East
3	1.89	3.27	1957-81	5.2	1930-81	e B	Avenue I and 10th Street East
4		1.23	1956-81	1.2	1956-81	D	Avenue K and 10th Street East
5		.42	1957-81	.4	1957-81	D	Avenue K and 10th Street West
6	1.29	1.38	1957-92	2.7	1930-92	e A	Avenue J-8 and Sierra Highway
7	1.59	4.51	1957-81	6.1	1930-81	e B	Avenue I and 15th Street West
8	1.59	4.40	1957-81	6.0	1930-81	e B	Avenue I and 15th Street West
9		-.27	1955-92	-.3	1928-92	A	Highway 138 and 87th Street East
10		-.23	1955-92	-.2	1935-92	A	Palmdale Boulevard and 47th Street East
11		-.23	1955-91	-.2	1955-91	C	Avenue M and 40th Street West
12		.29	1957-81	.3	1957-81	D	Avenue K and 50th Street West
13		3.46	1957-81	3.5	1957-81	D	Avenue J and 90th Street East
14		4.92	1957-81	4.9	1957-81	D	Avenue I and 90th Street East
15		4.63	1957-81	4.6	1957-81	D	Avenue I and 70th Street East
16		4.66	1957-81	4.7	1957-81	D	Avenue H and 90th Street East
17	1.80	2.17	1957-81	4.0	1930-81	e B	Avenue I and 20th Street East
18		-.19	1955-91	-.2	1955-91	C	Avenue M and 20th Street West
19		-.25	1955-92	-.3	1955-92	C	Avenue M and 30th Street West
20		-.16	1955-91	-.2	1955-91	C	Avenue M and 60th Street West
21		3.16	1957-81	3.2	1957-81	D	Avenue G and 60th Street East
22		1.90	1957-81	1.9	1957-81	D	Avenue F and 70th Street East
23		.23	1957-92	.2	1957-92	C	Avenue L-2 and Sierra Highway
24		.35	1957-92	.3	1957-92	C	Avenue K-8 and Sierra Highway
25		4.74	1957-92	6.0	1926-92	A	Avenue I and Sierra Highway
26	1.38	2.83	1957-92	4.2	1930-92	e A	Avenue G-2 and Sierra Highway
27		2.79	1957-92	3.5	1926-92	A	Avenue F-2 and Sierra Highway
28	1.05	2.61	1957-92	3.7	1930-92	e A	Avenue E-4 and Sierra Highway
29	.96	2.09	1957-81	3.1	1930-81	e B	Avenue E and Sierra Highway
30	.45	1.51	1957-92	2.0	1930-92	e A	Avenue C and Sierra Highway
31	.45	.84	1957-92	1.3	1930-92	e A	Avenue B and Sierra Highway
32		.23	1957-92	.2	1957-92	C	Avenue A and Sierra Highway
33		2.19	1957-81	2.2	1957-81	D	Avenue E and Division Street
34	1.50	1.02	1957-92	2.5	1940-92	e A	Avenue I and 45th Street West
35	1.80	2.30	1957-81	4.1	1930-81	e B	Avenue I and 30th Street West
36		3.15	1957-81	3.1	1957-81	D	Avenue J and 100th Street East
37		1.23	1957-81	1.2	1957-81	D	Avenue G and 30th Street East
38		1.30	1957-81	1.3	1957-81	D	Avenue E and 15th Street East
39		.95	1957-81	.9	1957-81	D	Avenue E and 30th Street East
40		.84	1957-81	.8	1957-81	D	Avenue E and 50th Street East

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Table 8. Calculated and estimated subsidence from about 1930 to 1992 for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Subsidence (ft)		Period of record, second period	Total subsidence, calculated or estimated (ft)	Period of record available	Code	Nearest cross streets or township/range location
	Estimated, first period	Calculated, second period					
41	1.77	4.21	1957-81	6.0	1930-81	e B	Avenue I and Sierra Highway
42	1.60	.68	1957-81	2.3	1940-81	e B	Avenue I and 50th Street West
43		.55	1957-81	.6	1957-81	D	Avenue K and 25th Street West
44		.42	1957-81	.4	1957-81	D	Avenue K and 35th Street West
45		1.19	1957-81	1.2	1957-81	D	Avenue I and 70th Street West
46		1.34	1957-92	2.3	1935-92	A	Avenue I and 75th Street West
47	1.34	1.04	1957-81	2.4	1940-81	e B	Avenue I and 90th Street West
48	1.50	.59	1957-81	2.1	1940-81	e B	Avenue G-8 and 90th Street West
49	1.50	.38	1957-81	1.9	1940-81	e B	Avenue F and 90th Street West
50	1.05	.27	1957-81	1.3	1930-81	e B	Avenue B-8 90th Street West
51	1.62	1.49	1957-81	3.1	1930-81	e B	Avenue B and 60th Street West
52		.80	1957-81	.8	1957-81	D	Avenue E and 60th Street West
53		1.43	1957-81	1.4	1957-81	D	Avenue G and 60th Street West
54		.81	1957-81	.8	1957-81	D	Avenue D and 80th Street West
55	-.14	.09	1960-81	-.1	1935-81	A	Pearblossom near 226th Street East
56		-.04	1955-81	.2	1929-81	B	Avenue O and 200th Street East
57		.08	1957-81	.3	1929-81	B	Avenue K-8 and 170th Street East
58		2.93	1957-81	2.9	1957-81	D	Avenue J and 110th Street East
59		1.30	1957-81	1.3	1957-81	D	Avenue J and 120th Street East
60		.38	1957-81	.4	1957-81	D	Avenue J and 130th Street East
61		.39	1957-81	.4	1957-81	D	Avenue J and 140th Street East
62		.05	1955-73	.1	1955-73	E	Avenue M and 150th Street East
63		.22	1955-81	.2	1955-81	D	Avenue H and 140th Street East
64		.12	1957-81	.1	1957-81	D	Avenue E and 140th Street East
65	.84	1.75	1957-92	2.6	1930-92	e A	Avenue E and 120th Street East
66		2.63	1957-81	2.6	1957-81	D	Avenue G and 90th Street East
67	1.11	3.04	1957-92	4.1	1930-92	e A	Avenue E and 90th Street East
68		4.01	1957-81	4.0	1957-81	D	Avenue E and 90th Street East
69	.99	5.41	1957-92	6.4	1930-92	e A	Avenue G-8 and 90th Street East
70		-.11	1955-91	-.1	1955-91	C	Avenue M and 90th Street East
71		.08	1957-81	.1	1957-81	D	Avenue D and 170th Street West
72		.08	1957-81	.1	1957-81	D	Avenue D and 210th Street West
73		.26	1957-92	.3	1957-92	C	Lancaster Road and 210th Street West
74	.63	.26	1957-92	.9	1930-92	e A	Lancaster Road and 160th Street West
75	.60	.11	1957-81	.7	1930-81	e B	Lancaster Road and 160th Street West
76	.50	.25	1957-81	.7	1940-81	e B	Lancaster Road and 140th Street West
77	.61	.16	1957-81	.8	1940-81	e B	Avenue I and 115th Street West
78	.89	.53	1957-81	1.4	1940-81	e B	Avenue I and 100th Street West
79		.04	1957-91	.0	1957-91	C	Johnson Road and Elizabeth Lake Road
80		-.21	1955-92	-.2	1955-92	C	Avenue O and 15th Street West

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Table 8. Calculated and estimated subsidence from about 1930 to 1992 for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Subsidence (ft) Estimated, first period	Subsidence (ft) Calculated, second period	Period of record, second period	Total subsidence, calculated or estimated (ft)	Period of record available	Code	Nearest cross streets or township/range location
81	0.57	2.31	1962-81	2.9	1930-81	e B	Avenue D and 20th Street West
82	1.26	.53	1961-92	1.8	1930-92	e A	Avenue D and 50th Street West
83		.05	1962-81	.1	1962-81	E	Highway 138 near 254th Street West
84		-.10	1962-92	-.1	1962-92	E	Lancaster Road and 270th Street West
85		.02	1962-92	.0	1962-92	E	Highway 138 and Old Ridge Road
86		-.06	1962-81	-.1	1962-81	E	Gorman Post Road
87		.32	1965-91	.3	1965-91	E	Avenue M and 20th Street East
88	.75	.35	1965-92	1.1	1930-92	e A	Avenue M and 60th Street East
89		.17	1965-92	.2	1965-92	E	Avenue M and 95th Street East
90		.18	1965-81	.2	1965-81	E	Avenue M and 110th Street East
91		.14	1965-81	.1	1965-81	E	Avenue M and 130th Street East
92		-.03	1965-91	-.0	1965-91	E	Avenue M and 90th Street West
93		-.04	1965-91	-.0	1965-91	E	Johnson Road and Elizabeth Lake Road
94		-.02	1965-92	-.0	1965-92	E	Johnson Road and Elizabeth Lake Road
95		.00	1965-91	.0	1965-91	E	Johnson Road and Elizabeth Lake Road
96		.01	1965-75	.0	1965-75	E	Avenue F-8 and 110th Street West
97	.72	2.57	1965-92	3.3	1930-92	e A	Avenue J and 95th Street East
98	1.47	.72	1965-92	2.2	1930-92	e A	Avenue E and 50th Street East
99	1.38	3.77	1961-92	5.2	1930-92	e A	Avenue I and 45th Street East
100		2.84	1965-81	2.8	1965-81	E	Avenue I and 50th Street East
101		2.11	1961-92	2.1	1961-92	C	Avenue E and 10th Street East
102	.96	.80	1965-81	1.8	1930-81	e B	Avenue A and 30th Street West
103	1.11	1.42	1965-92	2.5	1930-92	e A	Avenue A and 40th Street West
104	1.17	.98	1965-81	2.2	1930-81	e B	Avenue A and 45th Street West
105	1.29	.75	1965-81	2.0	1930-81	e B	Avenue A and 60th Street West
106	1.02	1.43	1965-81	2.4	1930-81	e B	Avenue F and 15th Street West
107	.84	1.47	1965-81	2.3	1930-81	e B	Avenue F and 30th Street West
108	.87	1.40	1965-81	2.3	1930-81	e B	Avenue F and 35th Street West
109	.96	1.51	1965-81	2.5	1930-81	e B	Avenue F and 40th Street West
110	.96	1.68	1965-81	2.6	1930-81	e B	Avenue F and 40th Street West
111	1.11	1.44	1965-92	2.5	1930-92	e A	Avenue A and 90th Street West
112	1.11	1.46	1965-81	2.6	1930-81	e B	Avenue A and 90th Street West
113	1.05	1.23	1965-81	2.3	1930-81	e B	Avenue A and 95th Street West
114		.18	1965-75	.2	1965-75	E	Avenue A and 110th Street West
115		1.14	1965-81	1.1	1965-81	E	Avenue H and 120th Street East
116		2.34	1965-81	2.3	1965-81	E	Avenue H and 110th Street East
117		1.80	1965-81	1.8	1965-81	E	Avenue F-8 and 120th Street East
118		1.64	1965-81	1.6	1965-81	E	Avenue K and 40th Street East
119		3.11	1965-81	3.1	1965-81	E	Avenue K and 50th Street East
120		.14	1965-81	.1	1965-81	E	Avenue G and 180th Street East

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Table 8. Calculated and estimated subsidence from about 1930 to 1992 for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Subsidence (ft) Estimated, first period	Subsidence (ft) Calculated, second period	Period of record, second period	Total subsidence, calculated or estimated (ft)	Period of record available	Code	Nearest cross streets or township/range location
121		0.15	1965-81	0.2	1965-81	E	Avenue E and 185th Street East
122		.15	1965-81	.2	1965-81	E	Avenue G and 185th Street East
123		.18	1965-81	.2	1965-81	E	Avenue I and 200th Street East
124		.18	1965-81	.2	1965-81	E	Avenue I and 180th Street East
125		-.04	1965-92	-.0	1965-92	E	Highway 138 and Fort Tejon Road
126		.20	1965-73	.2	1965-73	E	Avenue N and 60th Street East
127		.15	1965-81	.2	1965-81	E	Highway 138 and 126th Street East
128		.12	1965-81	.1	1965-81	E	Highway 138 and 175th Street East
129		.06	1965-92	.1	1965-92	E	Avenue P and 145th Street East
130		.08	1965-92	.1	1965-92	E	Palmdale Boulevard and 110th Street East
131		.12	1965-92	.1	1965-92	E	Avenue S-8 and 165th Street East
132	0.60	.30	1965-91	.9	1930-91	e A	Avenue M and 70th Street East
133		.50	1965-91	.5	1965-91	E	Avenue M and 40th Street East
134		.69	1968-81	.7	1968-81	E	Avenue K and 25th Street East
135		1.38	1968-81	1.4	1968-81	E	Avenue G and 15th Street East
136	.78	1.08	1968-81	1.9	1930-81	e B	Avenue C and 30th Street West
137		.05	1965-81	.1	1965-81	E	Avenue A and 190th Street West
138		.08	1965-81	.1	1965-81	E	Avenue A and 170th Street West
139		.14	1965-73	.1	1965-73	E	Avenue M and 215th Street East
140		.08	1972-81	.1	1972-81	E	Avenue E-8 and 200th Street East
141		.09	1972-81	.1	1972-81	E	Avenue E-8 and 200th Street East
142		.82	1965-92	.8	1965-92	E	Avenue A and 155th Street West
143		.02	1965-92	.0	1965-92	E	Avenue D and 110th Street West
144		.68	1972-81	.7	1972-81	E	Avenue E and 70th Street East
145		1.79	1972-81	1.8	1972-81	E	Avenue G-8 and 70th Street East
146		1.33	1972-81	1.3	1972-81	E	Avenue G-8 and 50th Street East
147		.20	1973-81	.2	1973-81	E	Avenue A and 140th Street West
148		.05	1973-81	.1	1973-81	E	Highway 138 and Gorman Post Road
149		.07	1973-92	.1	1973-92	E	Avenue N and Sierra Highway
150		.00	1973-91	.0	1973-91	E	Avenue M and Sierra Highway
151		-.01	1973-91	-.0	1973-91	E	Avenue M and Sierra Highway
152		-.08	1973-81	-.1	1973-81	E	Frazier Mtn. Park Road and Peace Valley Road
153	1.62	.67	1975-81	2.3	1930-81	e B	Avenue I and 30th Street East
154		.14	1973-91	.1	1973-91	E	Avenue M and 50th Street East
155		.11	1961-92	-.0	1926-92	A	Palmdale Boulevard and Sierra Highway
156		--		--			Township 8 North/Range 9 West Sec. 22
157	1.86	3.58	1965-92	5.4	1930-92	e A	Lancaster Boulevard and Sierra Highway
158	1.59	2.86	1965-92	4.5	1930-92	e A	Avenue H-4 and Sierra Highway
159		.84	1957-92	.8	1957-92	C	Avenue B and Sierra Highway
160		-.25	1955-92	-.3	1955-92	C	Highway 138 and Sierra Highway

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Table 8. Calculated and estimated subsidence from about 1930 to 1992 for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Subsidence (ft) Estimated, first period	Subsidence (ft) Calculated, second period	Period of record, second period	Total subsidence, calculated or estimated (ft)	Period of record available	Code	Nearest cross streets or township/range location
161		1.23	1961-92	1.2	1961-92	C	Township 9 North/Range 12 West Sec. 24
162		--		--			Township 9 North/Range 15 West Sec. 20
163		.11	1978-92	.1	1978-92	E	Township 6 North/Range 12 West Sec. 7
164		.08	1967-92	.1	1967-92	E	Jones Road and Lancaster Road
165		--		.4	1927-89	A	Rosamond Boulevard and Fitzgerald Boulevard
166		--		--			Township 9 North/Range 11 West Sec. 25
167		--		--			Township 8 North/Range 16 West Sec. 2
168		.00	1961-92	.0	1961-92	C	Township 9 North/Range 10 West Sec. 8
169		--		-.9	1926-88	A	Township 9 North/Range 19 West
170		-.25	1961-92	-.3	1961-92	C	Township 9 North/Range 12 West Sec. 8
171		.04	1961-92	.1	1937-92	A	Township 9 North/Range 10 West Sec. 11
172		--		.2	1937-92	A	Township 9 North/Range 10 West Sec. 20
173		.14	1973-89	.1	1973-89	E	Highway 58 and Rosamond Boulevard
174		.79	1973-89	.8	1973-89	E	Highway 58 and Clay Mine Road
175		--		--			Highway 58 and Clay Mine Road
176		.69	1961-92	.7	1961-92	C	Scout Road and Lancaster Boulevard
177		--		--			Scout Road and Lancaster Boulevard
178		--		--			Interstate 5 Lebec Rest Area
179		--		--			California Aqueduct and 204th Street East
180		--		--			Township 11 North/Range 6 West Sec. 32
181		--		--			Highway 138 and 116th Street East
182		-.23	1973-92	-.2	1973-92	E	Highway 58 and California City Boulevard
183		.37	1961-89	.5	1928-89	A	Township 10 North/Range 9 West
184		.08	1952-92	.1	1952-92	C	Highland Boulevard and Clay Mine Road
185		--		--			Highland Boulevard and Flint Road
186		.88	1959-92	2.6	1929-92	A	Avenue C and 20th Street East
187		.92	1959-89	2.5	1929-89	A	Avenue C and 50th Street East
188		--		1.3	1929-59	E	Avenue C and 80th Street East
189		3.03	1961-89	3.7	1929-89	A	Avenue B and 130th Street East
190		--		.3	1929-92	A	Avenue J and 180th Street East
191		--		.7	1929-92	A	Avenue G and 135th Street East
192		3.33	1961-92	3.3	1961-92	C	Avenue B and 140th Street East
193		.13	1973-92	.1	1973-92	E	Avenue B and 170th Street East
194		.10	1973-92	.1	1973-92	E	Avenue B and 200th Street East
195		.27	1973-92	.3	1973-92	E	Township 9 North/Range 9 West Sec. 14
196		.05	1973-92	.1	1973-92	E	Township 9 North/Range 9 West Sec. 11
197		--		--			Township 8 North/Range 8 West Sec. 34
198	0.93	3.10	1961-92	4.0	1930-92	e A	Avenue B and 120th Street East
199		--		--			Township 10 North/Range 9 West
200		--		--			Township 9 North/Range 9 West

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Table 8. Calculated and estimated subsidence from about 1930 to 1992 for 218 bench marks in Antelope Valley, Los Angeles and Kern Counties--*Continued*

Map No.	Subsidence (ft) Estimated, first period	Subsidence (ft) Calculated, second period	Period of record, second period	Total subsidence, calculated or estimated (ft)	Period of record available	Code	Nearest cross streets or township/range location
201		--		--			Township 9 North/Range 9 West Sec. 32
202		--		--			Township 10 North/Range 9 West Sec. 4
203		--		--			Township 10 North/Range 9 West Sec. 24
204		--		--			Township 8-9 North/Range 11-12 West
205		--		--			Township 8 North/Range 11 West Sec. 6
206		--		-0.1	1932-92	A	Highway 58 and 20 Mule Team Road
207		--		--			Highway 58 and 20 Mule Team Road
208		--		--			Township 10 North/Range 9 West
209		--		--			Township 9 North/Range 9 West Sec. 19
210		-0.06	1961-92	-.1	1961-92	C	Township 10 North/Range 10 West Sec. 23
211		--		--			Township 9 North/Range 9 West Sec. 27
212		-.07	1961-92	.1	1926-92	A	Rosamond Boulevard and Sierra Highway
213		1.04	1961-92	1.0	1961-92	C	Township 9 North/Range 11 West Sec. 20
214		.14	1961-92	.1	1961-92	C	Rosamond Boulevard and 50th Street West
215	1.23	2.58	1961-92	3.8	1930-92	e A	Avenue B and 80th Street East
216		-.08	1961-92	-.1	1961-92	C	Rosamond Boulevard and Lancaster Boulevard
217		-.09	1961-92	-.1	1961-92	C	Rosamond Boulevard near EAFB West Gate
218	1.80	2.44	1961-92	4.2	1930-92	e A	Avenue H-8 and 20th Street East

The starting year for estimates of subsidence for the bench marks coded "A" was 1930, except for one bench mark in Area 1 for which the starting year was 1940. The most recent measurement for all bench marks coded "A" was made between 1988 and 1992. The period of record for calculated subsidence for two bench marks coded with the letter "B"—corresponding to the square symbol in figure 8—was 1929-81. The period of record for estimated subsidence for all other "B"-coded bench marks started from either 1930 or 1940 and ended in 1981. Measurements for bench marks coded with letter "C"—corresponding to the triangle symbol in figure 8—were first done between 1952 and 1961 and most recently in 1991 or 1992. Measurements for bench marks coded with letter "D"—corresponding to the asterisk symbol in figure 8—were first done between 1955 and 1957 and all were most recently measured in 1981. Measurements for bench marks coded with letter "E"—corresponding to the plus symbol in figure 8—were made for all other time periods not included in the previous four categories. These periods ranged from 8 to 30 years, but generally spanned 15 years.

Although data for several periods are plotted on figure 8, more importance was given to bench marks with longer periods of record when the contours for areas with equal magnitudes of calculated or estimated subsidence were drawn. The contours indicate that a large area—210 mi^2 (542 km^2)—of Antelope Valley, generally bounded by Avenue K, Avenue A, 90th Street West, and 130th Street East, has subsided between 2 and 7 ft (fig. 8). Much of this same area, but only extending to 35th Street West, has subsided more than 3 ft, including a lobe that extends past 140th Street East at Avenue B. In an area south of Rosamond Lake, notably less subsidence has been measured than in surrounding areas. In this area, subsidence of less than 2.5 ft has been measured between 20th Street East and 70th Street East and Avenues C and G. More than 4 ft of subsidence has been measured in Antelope Valley in an L-shaped area with Avenue I as the long leg and 90th Street East as the short leg. In Area 2 near Sierra Highway, the area with more than 4 ft of subsidence is between Avenues G and J, but probably is limited to the area between Avenues H and J along most of the east-west axis of the L-shaped area. The western extent of the 4-ft subsidence contour is 30th Street West. Along the north-south axis, this contour extends about 1.5 mi east and west of 90th Street East between Avenues B and J, with a slight lobe extending to 120th Street East at Avenue B. Three areas identified on figure 1 had more than 5 ft of subsidence between about 1930 and 1992.

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The magnitudes of calculated or estimated subsidence are negligible in several areas. One of these areas of negligible subsidence is south of Avenue L, except for a small area between 40th Street East and 70th Street East at Avenue M where subsidence of between 0.5 and 1.1 ft was calculated or estimated. In another area, at 130th Street East and Avenue G, subsidence of 0.7 ft was measured between 1929-92. Less than 0.5 ft of subsidence has been measured in Antelope Valley east of 130th Street East, north of Rosamond Boulevard in the northeastern part of the valley, and west of 110th Street West, with some exceptions. Between 0.5 and 0.9 ft of subsidence was measured at four bench marks between 110th Street West and 160th Street West on Avenue I and Lancaster Road and at another bench mark at Avenue A and 155th Street West.

Average Rates of Subsidence for Selected Periods

To assess the variability of subsidence rates during the 1957-92 period and to relate the occurrence of subsidence to ground-water-level decline, shorter time periods were examined. The magnitudes and mathematically averaged annual rates of subsidence were calculated for six variable-length periods (table 9). The lengths of these periods were dependent on the years in which local network leveling had been done. These calculated rates of subsidence are annual averages and the rates could

Table 9. Magnitudes and average annual rates of subsidence for selected bench marks in Antelope Valley, Los Angeles County, for six variable-length periods between 1957 and 1992

[Map numbers refer to bench-mark locations in figures 7 or 8. ft, foot; ft/yr, feet per year; --, no data]

Map No.	Bench-mark name	1957-62		1962-65		1965-72		1972-75		1975-81		1981-92	
		Magnitude (ft)	Rate (ft/yr)	Magnitude (ft)	Rate (ft/yr)	Magnitude (ft)	Rate (ft/yr)	Magnitude (ft)	Rate (ft/yr)	Magnitude (ft)	Rate (ft/yr)	Magnitude (ft)	Rate (ft/yr)
1	BM 53	0.87	0.174	0.69	0.230	0.88	0.126	0.57	0.190	0.91	0.151	--	--
2	BM 56	--	--	.71	.238	.84	.119	.54	.181	.89	.149	--	--
3	BM 60	.66	.133	.55	.184	.74	.106	.50	.165	.82	.137	--	--
4	BM 73	.05	.011	-.04	-.014	.03	.004	.18	.059	.14	.023	--	--
5	BM 85	.14	.029	-.05	-.018	.08	.012	.14	.048	.10	.017	--	--
6	BM 118	.19	.038	.04	.012	.23	.033	.27	.091	.32	.053	0.33	0.030
7	BM 120	.91	.181	.79	.265	1.13	.161	.63	.210	1.06	.176	--	--
8	BM 121	.91	.181	.77	.257	1.11	.159	.62	.206	1.00	.166	--	--
9	BM 135	--	--	--	--	.14	.017	--	--	--	--	--	--
10	BM 171	--	--	--	--	.14	.018	--	--	--	--	.01	.000
11	BM 172	--	--	--	--	.06	.007	--	--	--	--	--	--
12	BM 185	.08	.017	-.05	-.017	.11	.016	.10	.032	.06	.010	--	--
13	BM 271A	.49	.098	.70	.233	--	--	--	--	.60	.101	--	--
14	BM 278A	.59	.118	.99	.330	--	--	--	--	1.00	.167	--	--
15	BM 283	.48	.095	.97	.322	1.49	.213	.75	.249	.95	.158	--	--
16	BM 287A	.46	.092	.97	.322	--	--	--	--	1.21	.201	--	--
17	BM 316	.40	.081	.30	.098	.46	.065	.39	.130	.62	.104	--	--
18	BM 330	--	--	--	--	.08	.010	--	--	--	--	--	--
19	BM 336	--	--	--	--	.06	.007	--	--	--	--	--	--
20	BM 397	--	--	--	--	.02	.003	--	--	--	--	.00	.000
21	BM 417	.61	.122	.41	.138	.94	.134	.56	.188	.63	.105	--	--
22	BM 426	.55	.109	.44	.148	-.10	-.014	.45	.150	.56	.094	--	--
23	BM 471	.01	.001	-.14	-.046	.00	.001	.17	.055	.05	.008	.02	.002
24	BM 472	.06	.012	-.10	-.033	.02	.003	.11	.037	0.16	.027	.10	.009
25	BM 474	1.02	.204	.69	.231	.90	.128	.54	.180	.81	.135	.67	.061
26	BM 476	.59	.117	.45	.148	.62	.089	.40	.132	.51	.084	.28	.025
27	BM 477	.50	.099	.39	.129	.64	.091	.45	.150	.58	.096	.23	.021
28	BM 479	.41	.083	.25	.082	.52	.074	.39	.130	.61	.101	.27	.025
29	BM 481	.34	.067	.19	.063	.52	.075	.45	.149	.60	.099	--	--
30	BM 482	.21	.042	.14	.048	.36	.051	.32	.105	.38	.063	.11	.010

Table 9. Magnitudes and average annual rates of subsidence for selected bench marks in Antelope Valley, Los Angeles County for six variable-length periods between 1957 and 1992--*Continued*

Map No.	Bench-mark name	1957-62		1962-65		1965-72		1972-75		1975-81		1981-92	
		Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)
31	BM 483	0.07	0.014	0.05	0.016	0.16	0.023	0.22	0.074	0.19	0.031	0.05	0.005
32	BM 484	.00	.000	.02	.005	.07	.010	.13	.043	.02	.004	.00	.000
33	BM 499	.46	.092	.21	.071	.53	.076	--	--	--	--	--	--
34	BM 537	.35	.070	.12	.040	.22	.032	.11	.035	.04	.006	.19	.017
35	BM 540	.60	.120	.40	.134	.54	.077	.32	.108	.43	.072	--	--
36	BM 545	.34	.069	.62	.205	1.13	.161	.52	.174	.54	.090	--	--
37	BM 560	.44	.088	-.02	-.008	.21	.030	.26	.086	.34	.057	--	--
38	BM 571	.47	.094	-.07	-.025	.23	.032	.32	.105	.36	.060	--	--
39	BM 577	.48	.095	-.17	-.058	.15	.021	.24	.081	.25	.042	--	--
40	BM 585	.52	.104	-.25	-.082	.11	.015	.23	.076	.23	.038	--	--
41	BM 666	1.00	.201	.73	.243	.97	.138	.71	.237	.80	.134	--	--
42	BM 714	.30	.059	.03	.009	.17	.025	.12	.041	.06	.010	--	--
43	BM 721	.12	.023	-.10	-.034	.13	.018	.16	.054	.25	.042	--	--
44	BM 725	.08	.016	-.13	-.043	.10	.014	.13	.043	.24	.040	--	--
45	BM 820	.30	.061	--	--	--	--	.12	.041	.07	.011	--	--
46	BM 823	.31	.061	.36	.119	.37	.053	.10	.034	.07	.011	0.13	0.012
47	BM 828	.30	.060	.32	.108	.31	.045	.08	.027	.01	.002	--	--
48	BM 835	.28	.056	.16	.052	.14	.021	.05	.017	-.04	-.007	--	--
49	BM 839	.25	.050	.08	.027	.04	.005	.04	.013	-.03	-.006	--	--
50	BM 852	.23	.047	.00	.000	-.05	-.007	.08	.025	.01	.002	--	--
51	BM 866	.28	.057	.31	.104	.47	.066	.25	.084	.17	.029	--	--
52	BM 878	.31	.062	.06	.019	.22	.032	.12	.038	.09	.015	--	--
53	BM 887	.29	.058	.30	.099	.42	.060	.20	.067	.22	.036	--	--
54	BM 900	.24	.049	.21	.070	.23	.032	.11	.035	.03	.005	--	--
55	BM 966	--	--	--	--	.07	.009	--	--	--	--	--	--
56	BM 998	--	--	--	--	.11	.013	--	--	--	--	--	--
57	BM 1069	.05	.010	-.14	-.046	-.01	-.002	.15	.051	.03	.005	--	--
58	BM 1078	.33	.066	.53	.177	.99	.141	.48	.160	.60	.099	--	--
59	BM 1082	.32	.064	.11	.037	.40	.057	.23	.077	.24	.040	--	--
60	BM 1087	.31	.061	-.20	-.068	.08	.012	.14	.046	.06	.011	--	--
61	BM 1090	.29	.058	-.18	-.060	.09	.013	.13	.042	.06	.009	--	--
62	BM 1103	--	--	--	--	.12	.015	--	--	--	--	--	--
63	BM 1146	--	--	-.34	-.114	.05	.007	.11	.037	.07	.011	--	--
64	BM 1155	.40	.080	-.41	-.136	.00	.000	.11	.035	.02	.003	--	--
65	BM 1159	.44	.088	-.12	-.039	.44	.062	.31	.105	.39	.066	.28	.026
66	BM 1165A	.50	.100	.30	.099	--	--	--	--	.71	.118	.41	.037
68	BM 1170A	.48	.096	.82	.272	--	--	--	--	.95	.158	--	--
69	BM 1171A	.46	.093	1.00	.334	--	--	--	--	1.14	.190	.66	.060
70	BM 1182	--	--	--	--	.15	.019	--	--	--	--	--	--
71	BM 1238	.00	.000	.16	.054	-.10	-.014	.00	.000	.01	.002	--	--
72	BM 1254	.00	.000	.23	.075	-.16	-.022	.00	.000	.01	.002	--	--
73	BM 1276	.00	.000	.19	.063	-.09	-.012	.00	.000	.05	.008	.11	.010
74	BM 1290	.00	.000	.17	.056	-.02	-.003	.00	.000	-.06	-.010	.17	.016
75	BM 1291	.00	.000	.16	.054	.02	.002	.00	.000	-.07	-.011	--	--
76	BM 1295	.00	.000	.15	.050	.02	.003	.00	.000	.08	.013	--	--
77	BM 1302	.11	.022	.04	.012	.01	.001	.01	.005	-.01	-.001	--	--
78	BM 1306	.22	.044	.12	.039	.16	.022	.02	.007	.02	.003	--	--
79	BM 1327	.00	.000	.04	.015	.00	.000	--	--	--	--	--	--
80	BM 1380	--	--	--	--	.10	.012	--	--	--	--	-.03	.002

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Table 9. Magnitudes and average annual rates of subsidence for selected bench marks in Antelope Valley, Los Angeles County for six variable-length periods between 1957 and 1992--*Continued*

Map No.	Bench-mark name	1957-62		1962-65		1965-72		1972-75		1975-81		1981-92	
		Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)
81	BM 1456	--	--	0.48	0.159	0.78	0.111	0.47	0.157	0.58	0.096	--	--
82	BM 1469	--	--	-.01	-.003	.10	.015	.12	.040	.08	.014	0.17	0.016
83	BM 1480	--	--	.16	.054	-.11	-.019	.00	.000	.00	.000	--	--
84	BM 1483	--	--	.03	.010	-.16	-.020	.00	.000	.01	.001	.02	.002
85	BM 1494	--	--	.11	.036	-.07	-.009	.00	.000	.00	.001	-.02	-.001
86	BM 1518	--	--	-.03	-.010	-.07	-.009	.00	.000	.05	.008	--	--
87	BM 2016	--	--	--	--	.24	.030	--	--	--	--	--	--
88	BM 2030	--	--	--	--	.31	.038	--	--	--	--	--	--
89	BM 2037	--	--	--	--	--	--	--	--	.00	-.001	.02	.002
90	BM 2041	--	--	--	--	--	--	--	--	.03	.005	--	--
91	BM 2045	--	--	--	--	--	--	--	--	.00	.000	--	--
92	BM 2061	--	--	--	--	.02	.002	--	--	--	--	--	--
93	BM 2067	--	--	--	--	.02	.002	--	--	--	--	--	--
94	BM 2076	--	--	--	--	.02	.003	--	--	--	--	--	.000
95	BM 2078	--	--	--	--	.01	.001	--	--	--	--	--	--
97	BM 2169	--	--	--	--	1.17	.167	.54	.180	.59	.098	.27	.024
98	BM 2174	--	--	--	--	.11	.016	.24	.079	.21	.035	.16	.015
99	BM 2180	--	--	--	--	1.15	.165	.66	.222	.85	.141	.32	.029
100	BM 2181	--	--	--	--	1.28	.182	.70	.234	.86	.144	--	--
101	BM 2186	--	--	--	--	.36	.051	.41	.137	.55	.091	.56	.051
102	BM 2230	--	--	--	--	.31	.045	.30	.101	.18	.031	--	--
103	BM 2235	--	--	--	--	.54	.077	.38	.128	.30	.050	.20	.018
104	BM 2236	--	--	--	--	.43	.062	.31	.104	.24	.040	--	--
105	BM 2244	--	--	--	--	.39	.056	.22	.075	.13	.022	--	--
106	BM 2290	--	--	--	--	.46	.065	.39	.129	.58	.097	--	--
107	BM 2295	--	--	--	--	.59	.084	.37	.125	.51	.084	--	--
108	BM 2298	--	--	--	--	.58	.083	.36	.121	.46	.076	--	--
109	BM 2300	--	--	--	--	.65	.094	.38	.128	.47	.079	--	--
110	BM 2301	--	--	--	--	.77	.110	.41	.138	.49	.082	--	--
111	BM 2317	--	--	--	--	.82	.117	.38	.127	.19	.032	.05	.004
112	BM 2318	--	--	--	--	.86	.123	.39	.131	.21	.035	--	--
113	BM 2319	--	--	--	--	.74	.105	.34	.114	.15	.025	--	--
115	BM 2344	--	--	--	--	.46	.065	.31	.103	.38	.063	--	--
116	BM 2348	--	--	--	--	1.11	.158	.54	.179	.70	.116	--	--
117	BM 2356	--	--	--	--	.78	.112	.43	.144	.58	.097	--	--
118	BM 2368	--	--	--	--	.75	.107	.49	.162	.41	.068	--	--
119	BM 2371	--	--	--	--	1.49	.213	.78	.260	.84	.140	--	--
120	BM 2393	--	--	--	--	.07	.010	.14	.045	-.06	-.010	--	--
121	BM 2395	--	--	--	--	.07	.010	.14	.046	-.05	-.009	--	--
122	BM 2396	--	--	--	--	.07	.010	.14	.046	-.05	-.009	--	--
123	BM 2409	--	--	--	--	.07	.010	.15	.049	-.03	-.005	--	--
124	BM 2442	--	--	--	--	.05	.007	.16	.055	-.03	-.006	--	--
125	BM 2616	--	--	--	--	.10	.012	--	--	--	--	.03	.003
126	BM 2646	--	--	--	--	.20	.025	--	--	--	--	--	--
127	BM 2678	--	--	--	--	.11	.014	--	--	--	--	--	--
128	BM 2685	--	--	--	--	.11	.014	--	--	--	--	--	--
129	BM 2706	--	--	--	--	.08	.010	--	--	--	--	.00	.000

Table 9. Magnitudes and average annual rates of subsidence for selected bench marks in Antelope Valley, Los Angeles County for six variable-length periods between 1957 and 1992--*Continued*

Map No.	Bench-mark name	1957-62		1962-65		1965-72		1972-75		1975-81		1981-92	
		Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)	Magni-tude (ft)	Rate (ft/yr)
130	BM 2716	--	--	--	--	0.13	0.016	--	--	--	--	-0.06	-0.005
131	BM 2746	--	--	--	--	.18	.022	--	--	--	--	-.06	-.006
132	BM 2760	--	--	--	--	.26	.032	--	--	--	--	--	--
133	BM 3198	--	--	--	--	.38	.047	--	--	--	--	--	--
134	BM 3225	--	--	--	--	--	--	0.26	0.088	0.26	0.043	--	--
135	BM 3294	--	--	--	--	--	--	.41	.136	.69	.116	--	--
136	BM 3317	--	--	--	--	--		.41	.137	.34	.057	--	--
137	BM 3387	--	--	--	--	-.01	-.001	--	--	.06	.011	--	--
138	BM 3392	--	--	--	--	.06	.008	.00	.000	.02	.003	--	--
139	BM 3398	--	--	--	--	.14	.017	--	--	--	--	--	--
140	BM 3454	--	--	--	--	--	--	.15	.049	-.06	-.011	--	--
141	BM 3455	--	--	--	--	--	--	.15	.049	-.05	-.009	--	--
142	BM 3549	--	--	--	--	.24	.030	.00	.000	--	--	--	--
144	BM 3646	--	--	--	--	--	--	.33	.109	.35	.058	--	--
145	BM 3724	--	--	--	--	--	--	.73	.245	1.06	.176	--	--
146	BM 3738	--	--	--	--	--	--	.57	.190	.76	.126	.39	.035
147	BM 3998	--	--	--	--	--	--	.00	.001	.20	.034	--	--
148	BM 4116	--	--	--	--	--	--	.00	.000	.05	.009	-.20	-.018
149	BM 4217	--	--	--	--	--	--	--	--	--	--	.02	.002
152	BM 4360	--	--	--	--	--	--	.00	.000	-.08	-.014	--	--
153	BM 4415	--	--	--	--	--	--	--	--	.67	.111	--	--

Table 10. Maximum magnitude and average annual rate of subsidence in Antelope Valley for six variable-length periods between 1957 and 1992

[ft, foot; ft/yr, feet per year]

Period	Magnitude (ft)	Rate (ft/yr)	Map No.	Bench-mark name	Nearest cross streets
1957-62	1.02	0.204	25	BM 474	Avenue I and Sierra Highway
1962-65	1.00	.334	69	BM 1171A	Avenue G-8 and 90th Street East
1965-72	1.49	.213	15	BM 283	Avenue I and 70th Street East
1972-75	.78	.260	119	BM 2371	Avenue K and 50th Street East
1975-81	1.21	.201	16	BM 287A	Avenue H and 90th Street East
1981-92	.67	.061	25	BM 474	Avenue I and Sierra Highway

have varied considerably within each period. The periods range from 3 to 11 years and are 1957-62, 1962-65, 1965-72, 1972-75, 1975-81, and 1981-92 (table 9). If data were not available for a bench mark for a specified year, leveling data from either the previous year or the following year were substituted and the number of years used to calculate the annual rate changed accordingly. Generalized contour maps showing average annual rates of subsidence were prepared for each of the periods (fig. 12).

The maximum magnitudes of calculated subsidence for the six variable-length periods ranged from 0.67 ft (11-year period) to 1.49 ft (7-year period), and the highest average annual rates of subsidence for the same periods ranged from 0.061 to 0.334 ft/yr (table 10). The maximum magnitudes of subsidence and average annual rates given in table 10 are for only one bench mark per period and are not representative of a widespread distribution. Contour maps showing magnitudes of subsidence for bench marks with a broad areal distribution are essential in determining the geographic extent of subsidence. However, the maximum rates of subsidence are representative of the relative scale of the changes in rates over time.

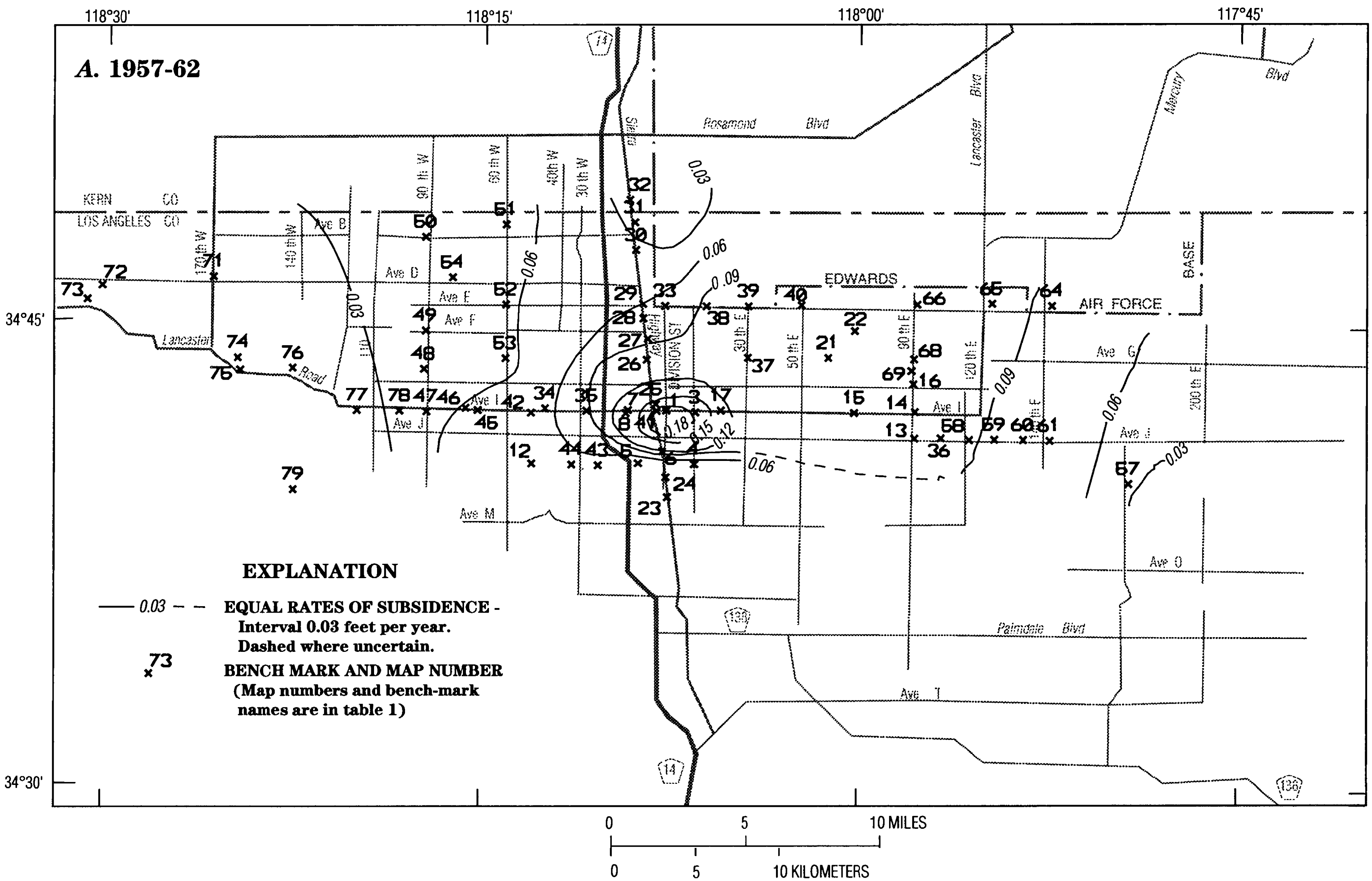

Figure 12. Average annual rate of subsidence in Antelope Valley for the period ***A***. 1957-62, ***B.*** 1962-65, ***C.*** 1965-72, ***D.*** 1972-75, ***E.*** 1975-81, ***F.*** 1981-92.

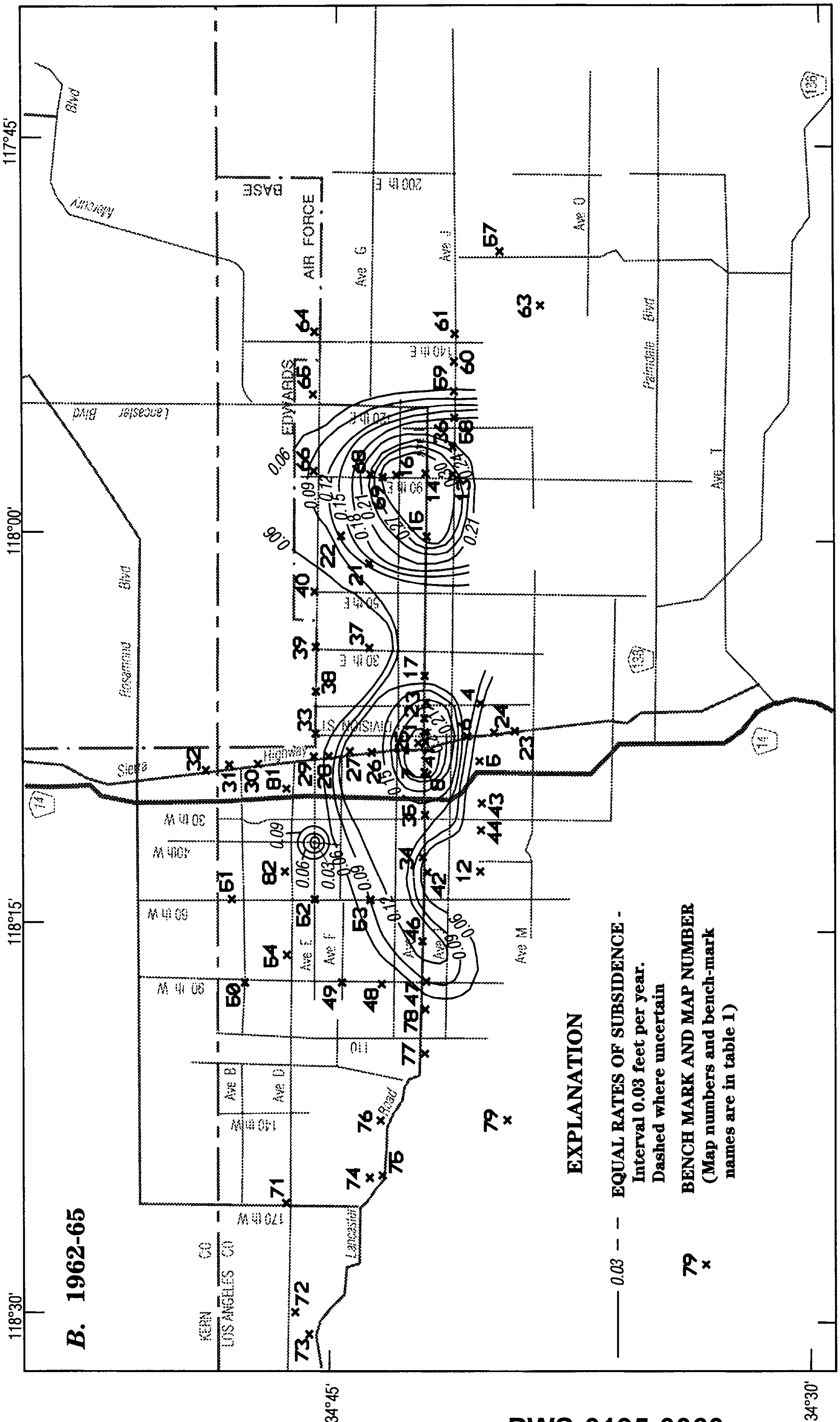

Figure 12. *Continued.*

PWS-0195-0060

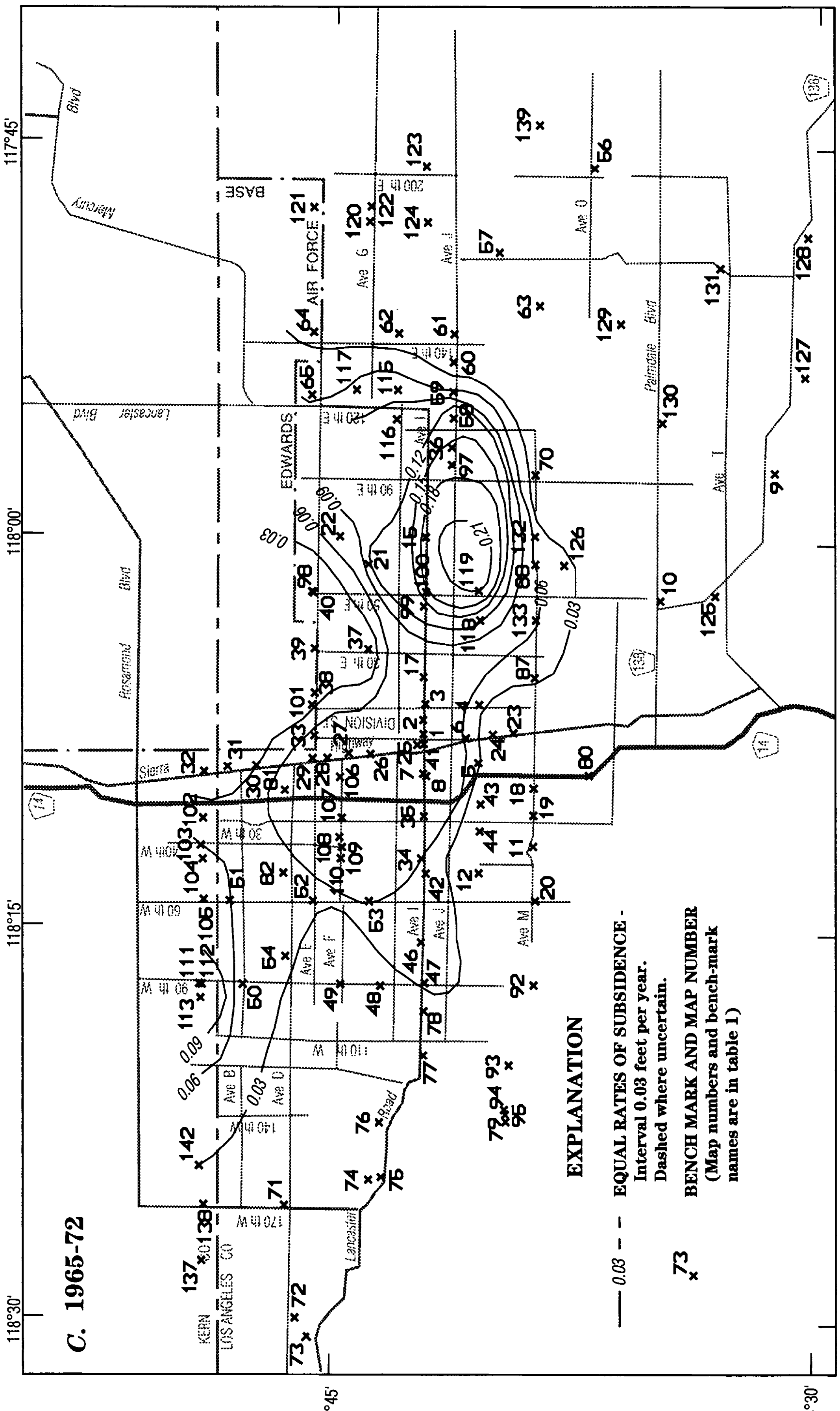

Figure 12. *Continued.*

PWS-0195-0061

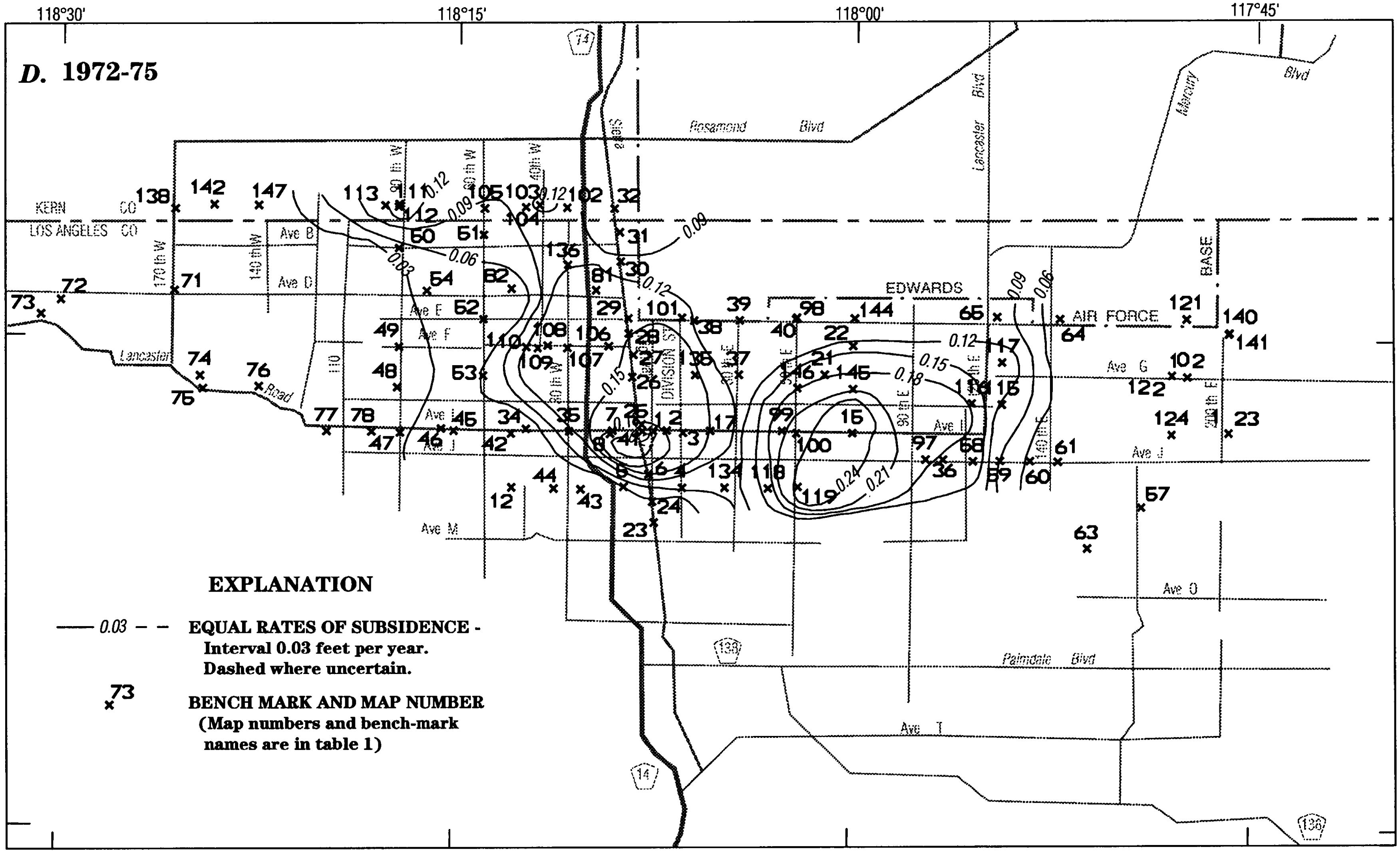

Figure 12. *Continued.*

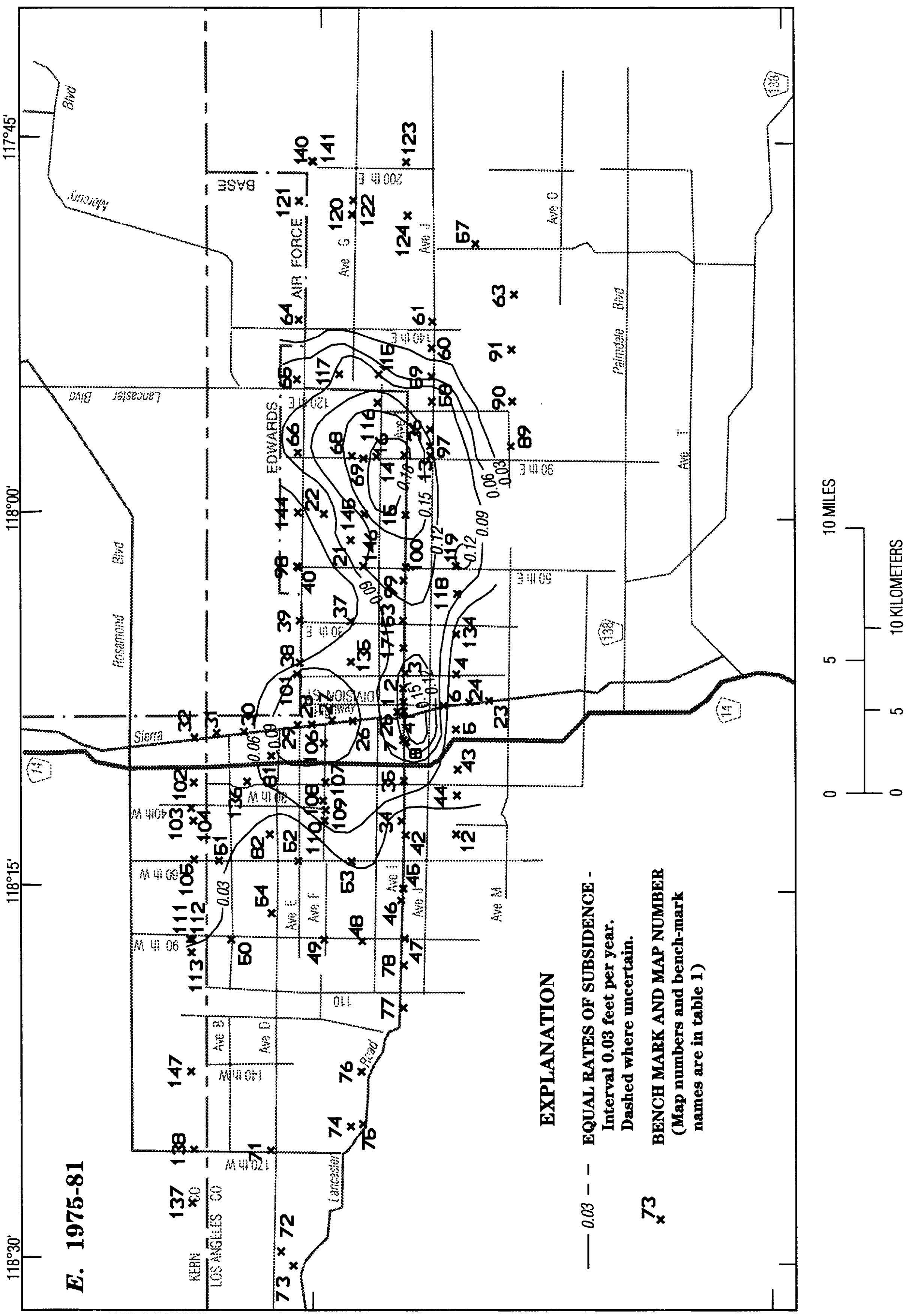

Figure 12. *Continued.*

PWS-0195-0063

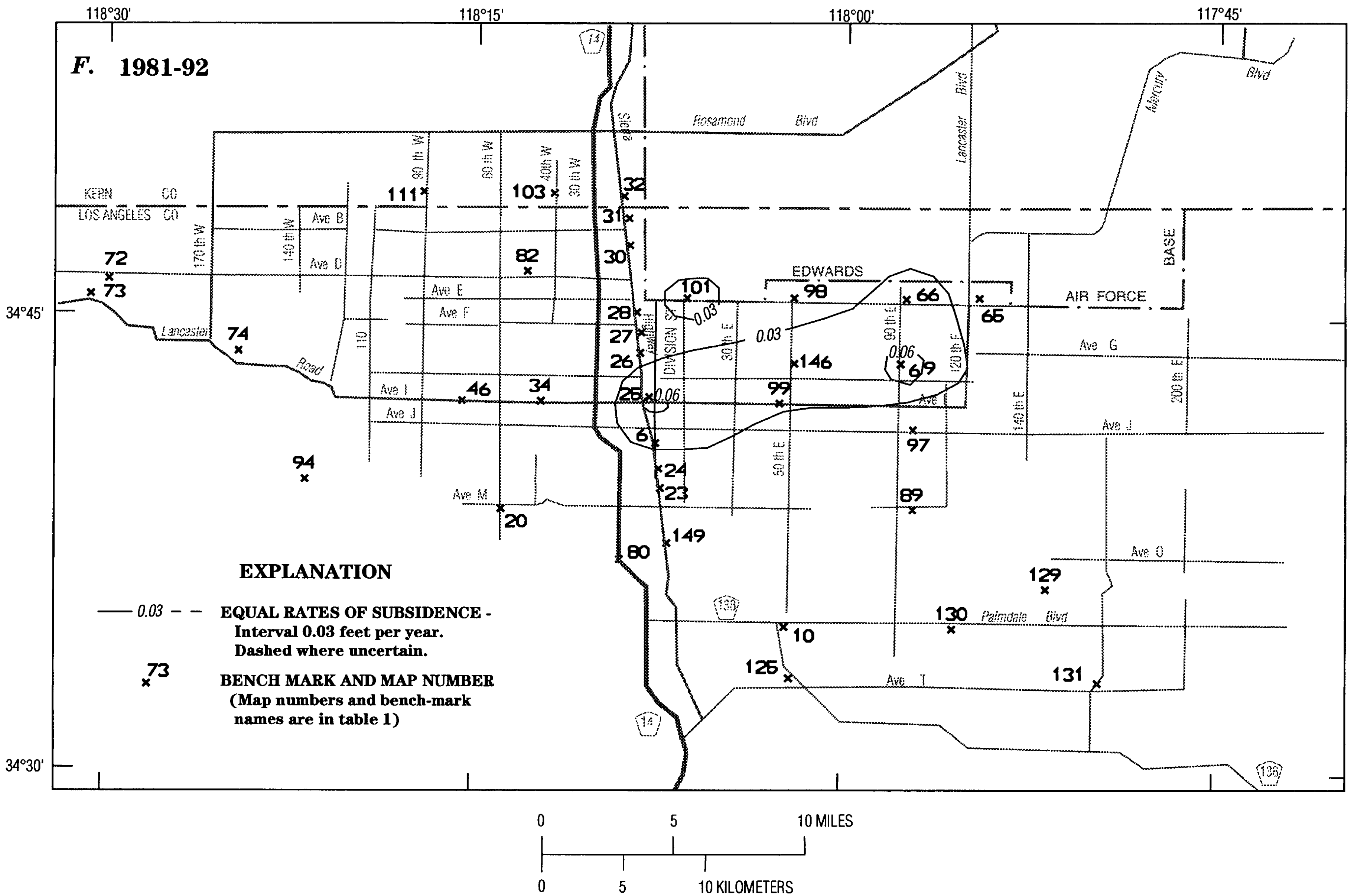

Figure 12. *Continued.*