UNITED STATES OF AMERICA

UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

CERTIFICATE OF EXACT COPY

Pursuant to 43 U. S. C. 1460, I hereby certify that the official records identified below are in the legal custody of the United States Geological Survey and attest that each annexed record is a true copy of a document comprising part of the official records of the United States Geological Survey: Land Subsidence and Problems Affecting Land Use at Edwards Air Force Base and Vicinity, California, 1990; Open File Report 92-4035; 1992 edition; "*this report has been scanned and reproduced*".

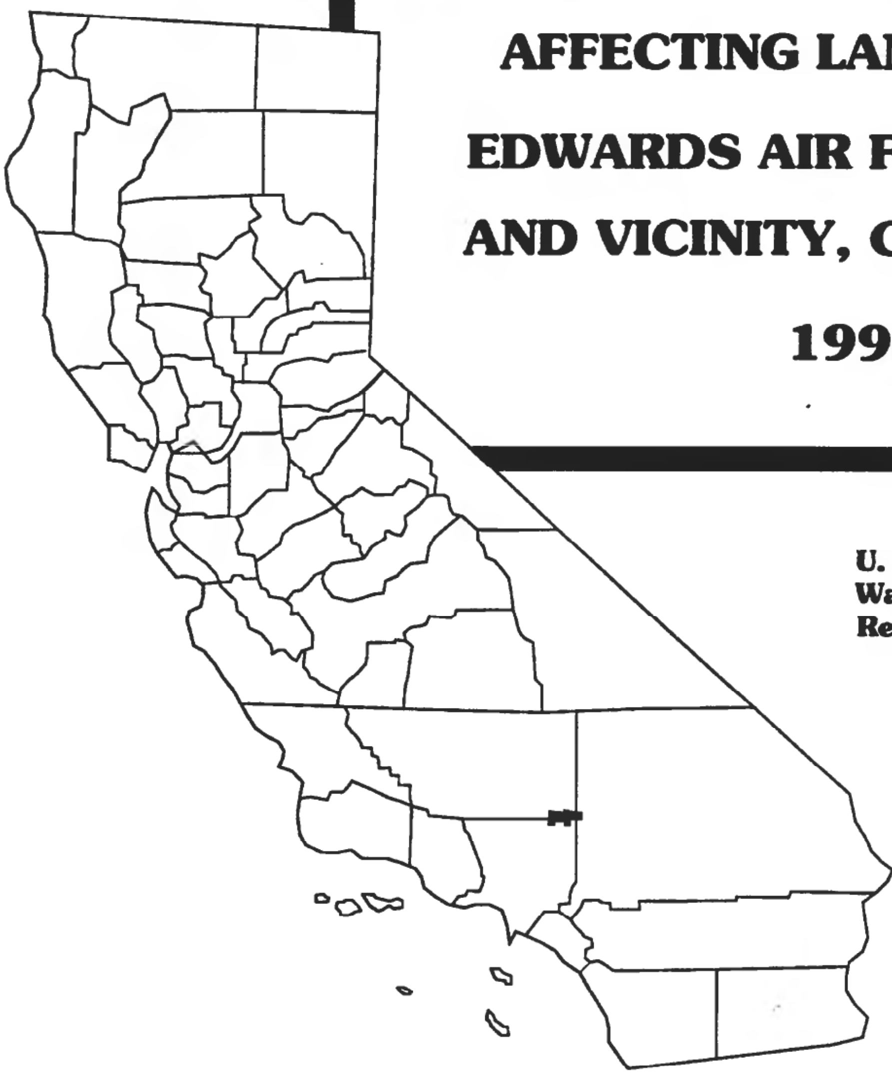
IN TESTIMONY WHEREOF, I have hereunto subscribed my name and caused the seal of the Geological Survey, Department of the Interior to be affixed, the day and year written below.

SIGNATURE: ....

TITLE: Business Partner Specialist..

OFFICE: ...United States Geological Survey..................................

LAND SUBSIDENCE AND PROBLEMS AFFECTING LAND USE AT EDWARDS AIR FORCE BASE AND VICINITY, CALIFORNIA, 1990



U. S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 92-4035

Prepared in cooperation with the
U.S. DEPARTMENT OF THE AIR FORCE

PWS-0193-0002

LAND SUBSIDENCE AND PROBLEMS AFFECTING LAND USE AT EDWARDS AIR FORCE BASE AND VICINITY, CALIFORNIA, 1990

By James C. Blodgett *and* J.S. Williams

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 92-4035

Prepared in cooperation with the

U.S. DEPARTMENT OF THE AIR FORCE

7210-19

Sacramento, California
1992

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

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

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

For additional information write to:
District Chief
U.S. Geological Survey
Federal Building, Room W-2233
2800 Cottage Way
Sacramento, CA 95825

CONTENTS

FIGURES

PWS-0193-0005

TABLES

Conversion Factors and Vertical Datum

Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per year (ft/yr)	0.3048	meter per year
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Vertical Datum

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

PWS-0193-0006

LAND SUBSIDENCE AND PROBLEMS AFFECTING LAND USE AT EDWARDS AIR FORCE BASE AND VICINITY, CALIFORNIA, 1990

By James C. Blodgett *and* J.S. Williams

Abstract

Land subsidence in Antelope Valley, which includes Edwards Air Force Base, was first reported in the 1950's; by 1967, about 200 square miles of Antelope Valley were affected by as much as 2 feet of subsidence. Prior to 1973, subsidence on the base was not considered significant. To determine the significance of current land subsidence conditions at Edwards Air Force Base and vicinity, a vertical-control network with 41 bench marks was surveyed in 1989 using the Global Positioning System. This network was developed to provide an areawide basis for comparing historic changes in bench-mark elevation on the basis of selected stable bench marks. Accuracy of the ellipsoidal height for the surveyed area, based on North American Datum 1983 (NAD 83), relative to sea level, is about 0.1 foot. Four bench marks that were unaffected by subsidence and with known geoidal heights were used in adjusting the Global Positioning System surveys to sea-level datum.

Differential levels to third-order standards of accuracy were surveyed for 65 bench marks in 1989-91 to determine the areal distribution of subsidence. Measured land subsidence ranged from 3.3 feet along the southern edge of Edwards Air Force Base to about 0.3 foot on the northern edge. A gradual decline of ground-water levels, more than 90 feet at some wells since 1947, is associated with the land subsidence. The amount of land subsidence at the base varies depending on the relative quantities of water pumped from various well fields and the differences in geologic substrata. This is shown by varying amounts of subsidence near the western edge of Rogers Lake. Near the southern edge of Rogers Lake, the land subsided more than 2 feet between 1961 and 1989. The average rate of land subsidence near the south end of Rogers lakebed is about 0.1 foot per year.

Land subsidence is causing surface deformation at Edwards Air Force Base and surrounding areas. This deformation has caused the formation of sinklike depressions, fissures, and cracks on Rogers lakebed. These changes adversely affect the use of the lakebed as a runway for airplanes and space shuttles. Repairs to the lakebed have been unsatisfactory because the load-carrying capacity of the repaired lakebed is less than that of the original lakebed. Continued active surface deformation further adversely affects repairs that are made to the runways.

Fissures are a major concern because they may extend to the water table, allowing direct access for contamination by toxic materials. In addition, existing sinklike depressions, fissures, and cracks on the lakebed may not be detected until aircraft or space shuttles exceed the load capacity of the soil. When the lakebed floods, as during periods of flooding in January and March 1991, the sinklike depressions and fissures become avenues of vertical water movement. Changes in lakebed slope and continued land subsidence contribute to the formation of new drainage channels on the lakebed. These channels, which form patterns collectively called desert flowers, increase in size and density following periods of precipitation or lakebed flooding.

INTRODUCTION

Land subsidence is a long-term phenomenon in the Antelope Valley area of California (Poland, 1984, p. 6-7; Holzer, 1986, p. 748). In 1988, land subsidence was noted at Edwards Air Force Base (AFB) (fig. 1). In the Antelope Valley, subsidence is attributed to compaction of fine-grained materials in the aquifer system that are dewatered because of ground-water pumping. Aseismic (nonearthquake) deformation of the land surface, which appears in the form of sinklike depressions, fissures, and cracks, is commonly associated with regional land subsidence. Some of these surface deformations on Rogers lakebed result in formation of drainage channels along the trace of the fissures (fig. 2). Changes on the lakebed adversely affect the use of the lakebed surface for landing airplanes and space shuttles.

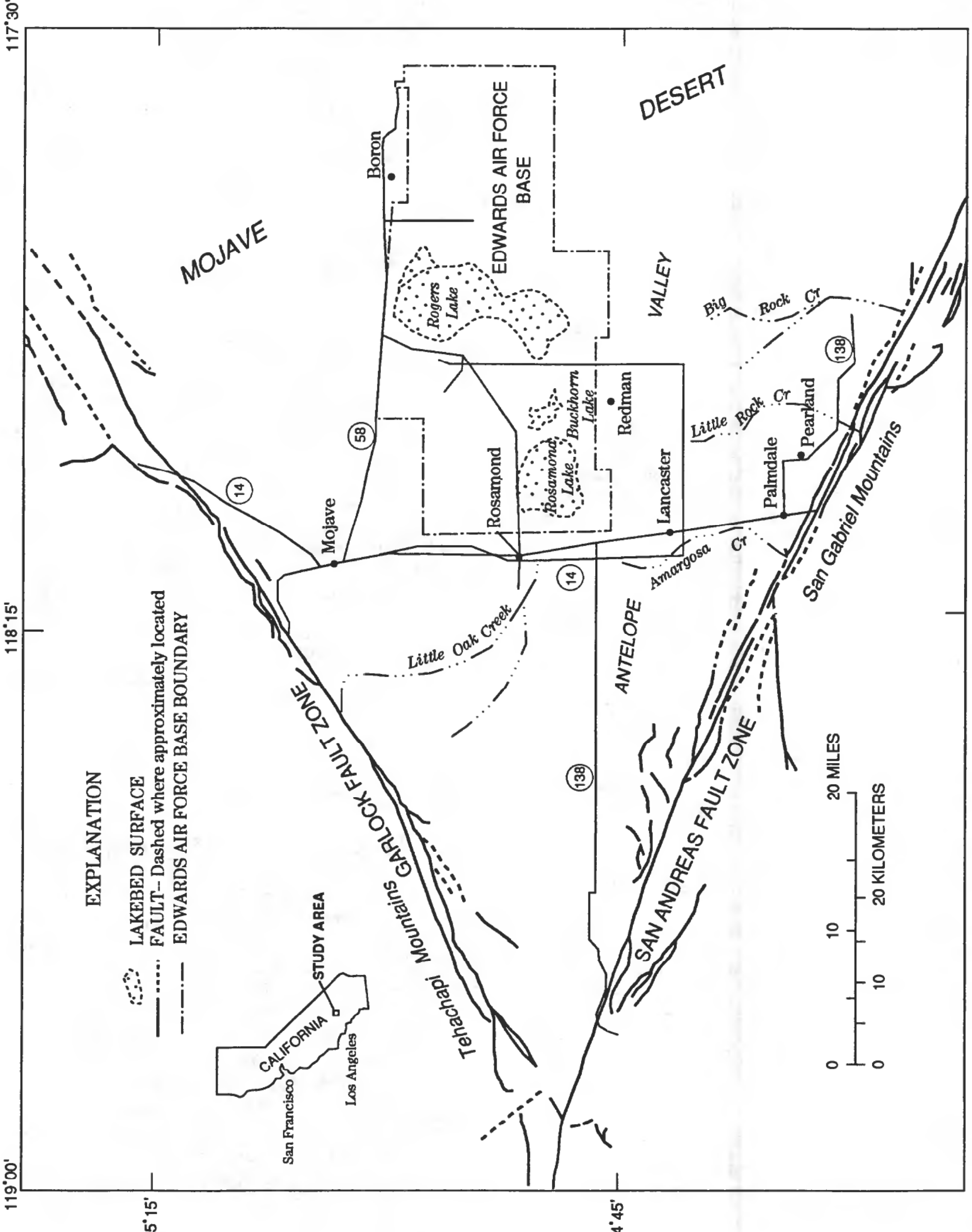


Figure 1. Location of Edwards Air Force Base.

PWS-0193-0008

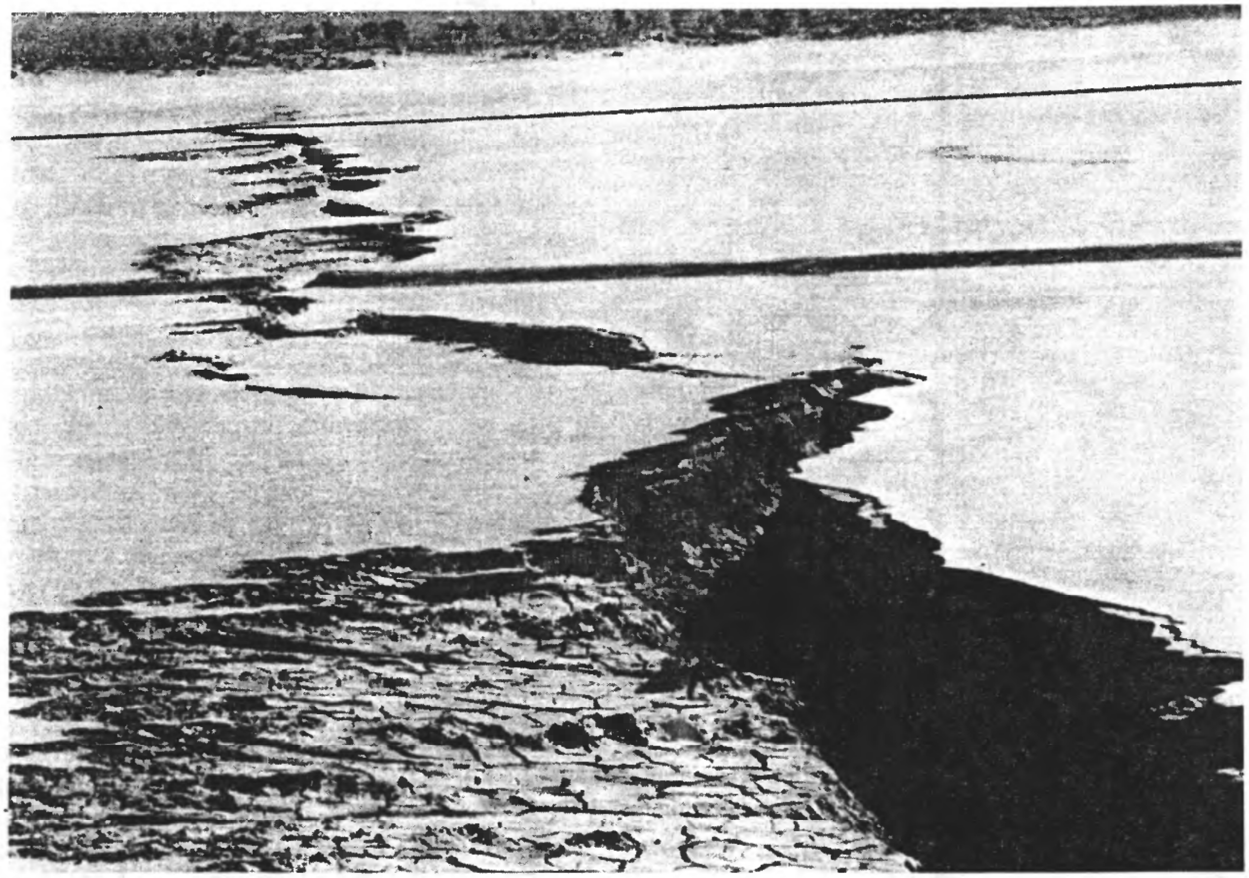


Figure 2. Fissure across Runway 25 on Rogers lakebed after January 1991 flooding. This fissure also is a drainage channel and point of infiltration to ground water. Note cracks that form small polygons on eroded area near fissure. Width of fissure at land surface is as much as 10 feet. Photograph courtesy of U.S. Air Force, February 1991.

Expenditures to date (1990) for runway repair have been high, and the repairs have been somewhat ineffective (Melvin Marmet, U.S. Air Force, oral commun., July 1991). The load-carrying capacity of the repaired lakebed is less than that of the original lakebed, and active deformation continues to adversely affect the repairs. Evidence of new sinklike depressions and fissures indicates that the lakebed is being subjected to continuing land-surface deformation.

The purpose of this report is to present the results to date of recent studies done by the U.S. Geological Survey, in cooperation with the U.S. Department of the Air Force, to determine the cause and areal extent of land subsidence and surface deformation on Rogers lakebed and vicinity, and the effects of surface deformation on runways used for aircraft landings at Edwards AFB in southern California. Because of the time-related effects of land subsidence, several years of data collection will be needed to establish subsidence trends and evaluate those factors causing land subsidence. Land subsidence was noted previously near Lancaster, which is near the base (Lofgren, 1966; Lewis and Miller, 1968; Poland, 1984, p. 6-7). Thus, selected off-base sites were included for data collection and analysis to determine if land subsidence is continuing near the base and if near-base ground-water pumping may be contributing to land subsidence and surface deformation on the base.

DESCRIPTION OF STUDY AREA

Antelope Valley, about 60 mi north of Los Angeles, California in the northwestern part of the Mojave Desert (fig. 1), has an arid environment. Historically, water supplies have been obtained primarily by pumping ground water. The valley is a closed, inland drainage basin covering about 2,400 mi^2. The Tehachapi Mountains, with elevations to 8,000 ft above sea level, form the northwestern border; the San Gabriel Mountains, with elevations to 10,000 ft, form the southwestern border. Average elevation of the valley floor is about 2,500 ft. Mean annual precipitation at Palmdale on the valley floor, based on records between 1933 and 1989, is 7.5 inches. The Tehachapi and San Gabriel Mountains are barriers against the prevailing west-to-east movement of storms from the Pacific Ocean. As a result, the quantity of precipitation in Antelope Valley shows a rainshadow effect; average annual precipitation ranges from 25.6 inches in the west part of Antelope Valley to 4.8 inches at Edwards AFB near Rogers Lake. Most streamflow occurs during the winter months, November through March. Runoff from uplands enters the valley floor through various creeks, and excess flows follow unpredictable paths across the valley floor toward Rogers, Buckhorn, and Rosamond Lakes (fig. 1).

The aquifer system in Antelope Valley was described by Durbin (1978) as a ground-water basin with a surface area of 900 mi^2 and a thickness of as much as 5,000 ft beneath the valley floor. The ground-water system consists of two alluvial aquifers separated by fine-grained lacustrine deposits. Runoff from the Tehachapi and San Gabriel Mountains serves as the principal sources of ground-water basin recharge.

Historically, water supplies for the valley have been obtained primarily by pumping ground water. During 1922-90, ground-water pumping in excess of natural recharge has resulted in a steady decline of the ground-water level in the basin. Beds of silt and clay material (lacustrine deposits) that are subject to compaction when dewatered are interspersed throughout the alluvial aquifer system in the valley. Poland (1984, p. 10) indicated that the range of depth of these beds is between 200 and 1,000 ft. Land subsidence is associated with declining ground-water levels caused by pumping and the presence of beds of fine-grained (lacustrine) material that are subject to compaction.

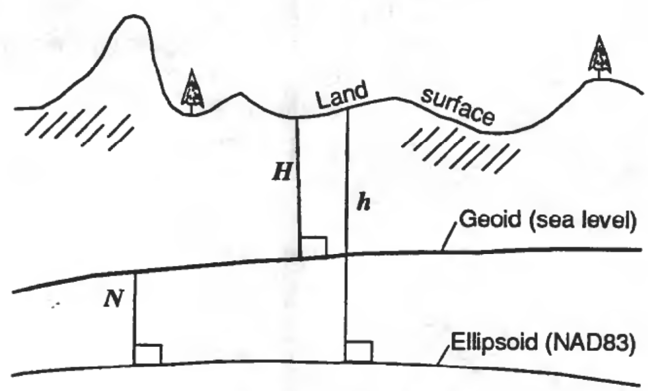
MEASUREMENT OF LAND SUBSIDENCE

Land subsidence in Antelope Valley was first reported by Lewis and Miller (1968) after several differential leveling survey lines through Rosamond, Palmdale, and Redman (fig. 1) were compared. Between 1955 and 1967, about 200 mi^2 in Antelope Valley were affected by land subsidence, with subsidence of 1.8 ft in Lancaster (fig. 1) and more than 2 ft in two areas 6 to 10 mi east of Lancaster.

GLOBAL POSITIONING SYSTEM SURVEYS

Global Positioning System (GPS) surveys were used to establish vertical-control data at Edwards AFB and vicinity in March 1989. GPS, described by Collins (1989), is a U.S. Department of Defense satellite-based navigation system designed to provide worldwide positioning capability. Field equipment consisted of an antenna and a receiver-processor unit, which also records data on a cassette tape. Precise relative positions of two or more bench marks are determined from satellite-tracking data received simultaneously at each bench mark.

Elevations for selected bench marks were computed by calculating the separation (distance *N*, fig. 3) of GPS ellipsoidal heights from the geoid, which is the equipotential surface coinciding with sea level. The geoidal separation, relative to sea level, ranges from about 59 to 131 ft in the conterminous United States (Collins, 1989). These elevations can then be compared with those from earlier differential leveling surveys to calculate the amount of subsidence to date.



EXPLANATION

h Ellipsoidal height, referenced to the ellipsoid

H Land-surface elevation, referenced to the geoid, or sea level

N Geoid separation, NAD83—North American Datum 1983

Figure 3. Relation of ellipsoidal, geoidal, and land-surface heights (from Blodgett and others, 1990).

PWS-0193-0010

Bench-mark elevations referenced to sea level cannot be defined by GPS surveys without accurate measurements of the applicable amount of geoidal separation to the study area. Changes in elevation caused by land subsidence, however, are equivalent to changes in ellipsoidal height obtained during successive GPS surveys. Changes in ellipsoidal height can be measured by repeat GPS surveys; accuracy is limited only by the inherent errors in the GPS technique, presently about 1.5 ppm (parts per million) of the distance between bench marks (Bock and others, 1984).

One of the objectives of the GPS surveys at Edwards AFB has been to establish a precise network of bench marks with coordinates defined by GPS to monitor land subsidence through future GPS surveys. The GPS network is designed to include stable bench marks on bedrock and at other locations to reference the network in the horizontal planes (*x*, *y* coordinates) and vertical planes (*z* coordinate). For the 1989 GPS survey, bench marks Buckhorn, F1147, and Y1139 on bedrock and bench mark 6MDC, which is about 7 mi from pumped wells within the project area, were used as stable sites (fig. 4). In the course of GPS surveying, precise horizontal coordinates also have been determined for all bench marks.

The selection of bench marks included in the GPS survey was based on one or more of the following criteria:

- Bench marks were referenced for a long period of time by differential level surveys.
- Some bench marks are on bedrock to use as reference sites.
- Bench marks are in areas of suspected subsidence.
- Visibility of the satellites from the bench marks is unobstructed. At some locations, alternative (offset) bench marks were installed.

The GPS-network design for the survey of Edwards AFB includes 41 bench marks (fig. 4, table 1), including stable bench marks on the periphery of the project area and bench marks in areas affected by land subsidence within the project area. GPS measurements were obtained at selected bench marks that recently had been surveyed in order to calculate the geoidal separation. GPS observations were obtained from at least four satellites for a period of 4 hours and 50 minutes at each bench mark. The GPS data are of excellent quality, except those collected on March 14, 1989, when an extreme solar flare caused a considerable amount of ionospheric noise.

Processing and analysis of the GPS data were completed using the broadcast ephemeris. The computed vectors between bench marks and the satellites are combined in a least-squares adjustment using weights that are the standard errors (typically 0.02 ft in each component) estimated in the PHASAR vector computations. The vectors then were adjusted holding bench mark Buckhorn fixed in all three components and bench marks F1147, Y1139, and 6MDC fixed in their ellipsoidal heights (fig. 4). These bench marks were selected because consistent elevations for these bench marks are known. The Rapp 360 geopotential model (Rapp and Cruz, 1986) was used to adjust the published elevations to obtain the geoid heights. For this adjustment, the survey network was rotated along the *x* and *y* axes. This fit the GPS system with a network of local coordinates that are based on published elevations of bench marks Buckhorn, F1147, Y1139, and 6MDC. As a final step, the geoid heights obtained from this adjustment for geoid separation were corrected to give the best estimate of current bench-mark elevations in the network.

DIFFERENTIAL LEVELING SURVEYS

Differential (conventional) leveling surveys between selected bench marks during 1989-91, plus those included in the 1989 GPS surveys were used to determine the magnitude, areal extent, and approximate rates of land subsidence at Edwards AFB and vicinity. Differential leveling surveys to various bench marks in the survey area (figs. 5 and 6, tables 1 and 2) were of first-, second-, or third-order standards of accuracy, as defined by the National Oceanic and Atmospheric Administration (1980). Although first- or second-order-accuracy surveys were done in 1926, 1947, 1955, 1961, 1965, and 1973, most of the recent surveys are of third-order or better accuracy (1989-91) or were derived from GPS surveys (1989). These were done to establish a recent vertical-control network for the study area.

PWS-0193-0011

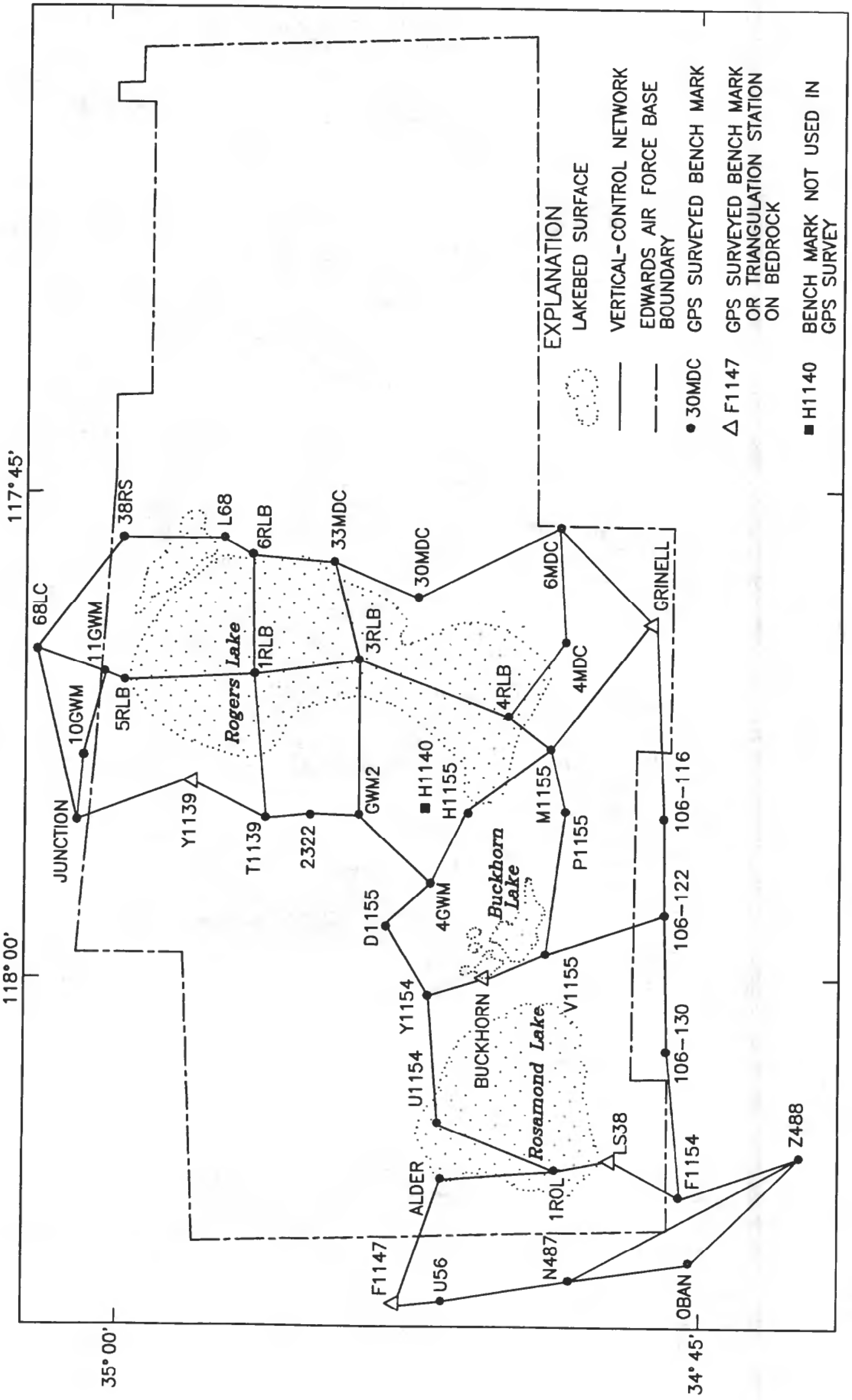


Figure 4. Global Positioning System (GPS) survey control network, March 1989.

PWS-0193-0012

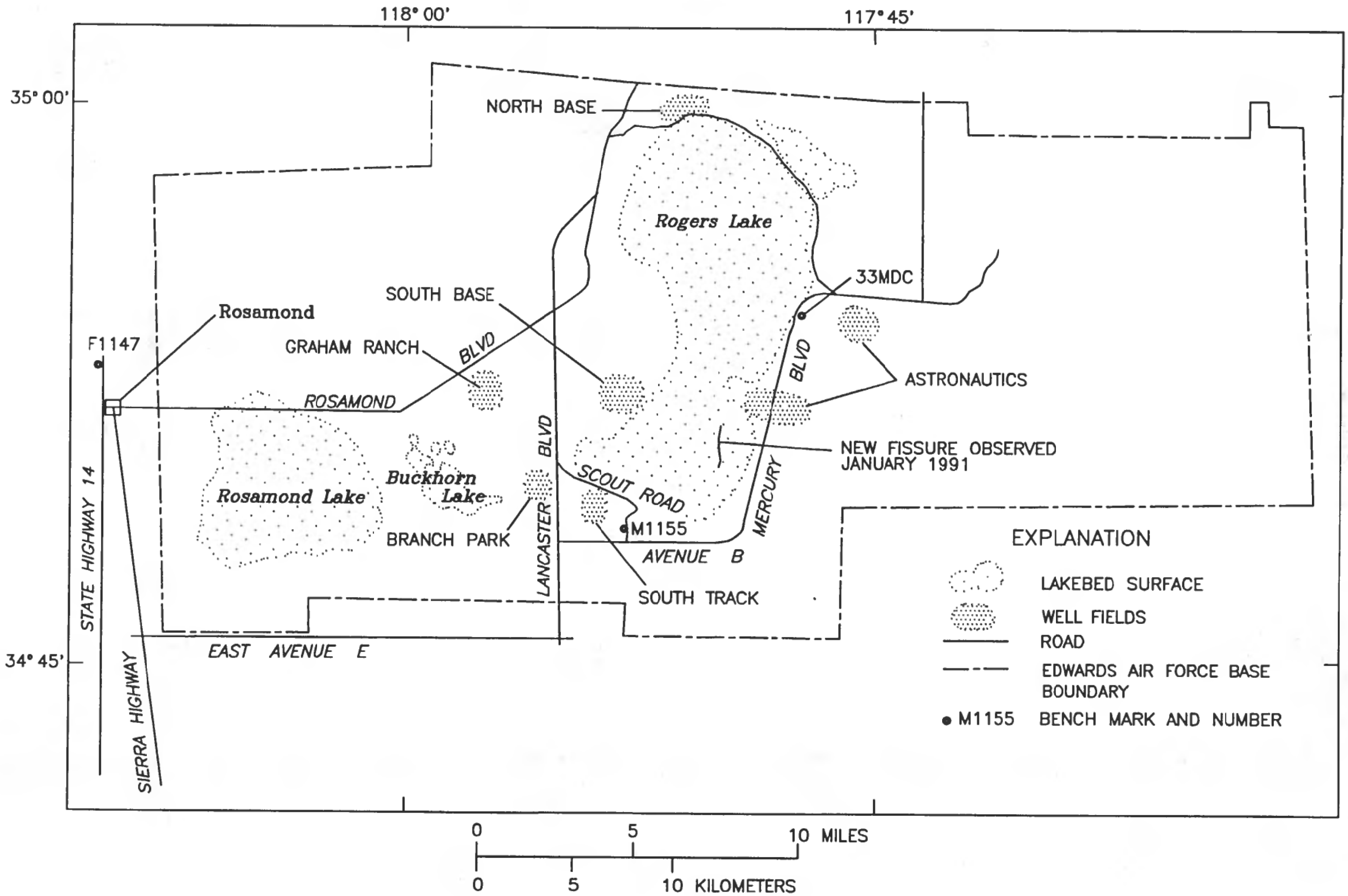


Figure 5. Location of well fields, newly observed fissure, and selected bench marks.

PWS-0193-0013

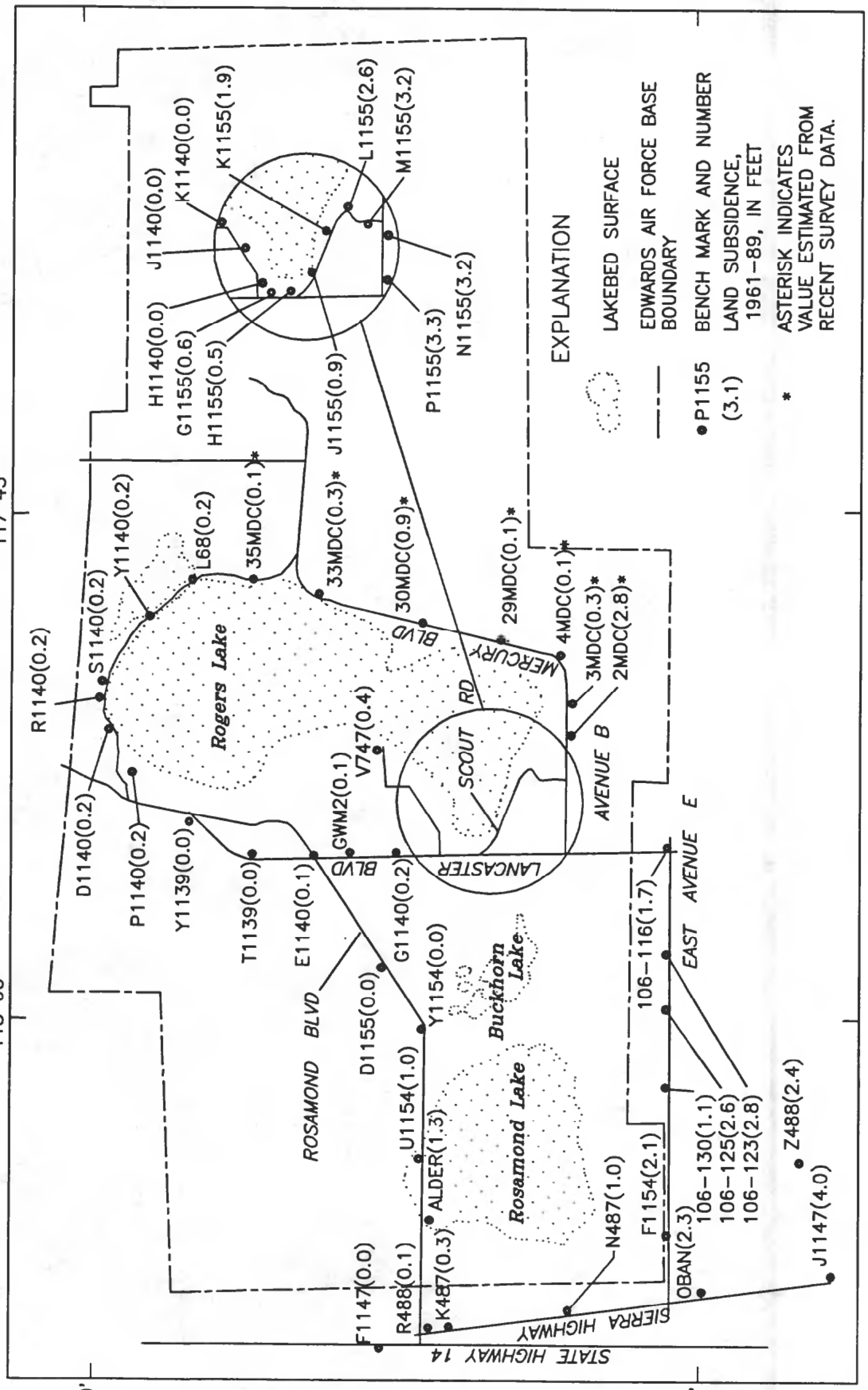


Figure 6. Subsidence (1961-91) at selected bench marks.

PWS-0193-0014

Table 1. Global Positioning System (GPS) bench marks, GPS and differential leveling survey elevations, and difference between 1961 and 1989-91 surveys

[NGS, 1961: First or second order surveys by National Geodetic Survey. USGS, 1973: First or second order surveys by U.S. Geological Survey. USGS, 1989-91: Third order surveys by U.S. Geological Survey. --, no data; nc, not calculated]

GPS bench mark	Elevation, in feet above sea level				Difference between 1961 and 1989-91
	NGS 1961	USGS 1973	GPS survey March 1989	USGS 1989-91	
F1147[1]	2,447.32	2,447.32	2,447.32	--	0
U56	2,325.96	2,325.88	2,325.82	--	.1
N487	2,305.99	2,305.28	2,305.04	--	1
OBAN	2,305.19	2,303.51	2,302.92	--	2.3
Z488	2,364.57	--	2,362.17	--	2.4
ALDER	2,275.96	2,275.25	2,274.63	--	1.3
U1154	2,274.98	2,274.28	2,273.98	--	1
1ROL	--	--	2,273.31	--	nc
F1154	2,303.45	2,302.57	2,301.31	--	2.1
106-130	2,318.85	2,318.44	2,317.71	--	1.1
106-122	2,343.64	2,342.27	2,340.60	--	3
106-116	2,358.14	2,357.34	2,356.46	--	1.7
GRINELL	--	--	3,174.17	--	nc
V1155	2,298.76	--	2,296.12	--	2.6
BUCKHORN	--	2,401.01	2,401.01	--	nc
Y1154	2,408.36	2,408.23	2,408.39	--	0
D1155	2,378.07	2,377.90	2,378.05	--	0
4GWM	--	2,322.69	2,322.37	--	nc
H1155	2,280.64	2,280.34	2,279.94	--	.7
M1155	2,300.82	2,299.57	2,297.63	2,297.66	3.2
P1155	2,311.64	2,310.40	2,308.53	2,308.35	3.3
4MDC	--	2,332.29	2,332.15	2,332.15	nc
6MDC	--	2,602.38	2,602.39	--	nc
GWM2	2,302.24	2,302.09	2,302.10	--	.1
3RLB	--	--	2,271.75	--	nc
30MDC[2]	2,292.45	2,291.89	2,291.40	2,291.52	.9
33MDC[2]	2,278.93	2,278.87	2,278.67	2,278.64	.3
2322	--	--	2,321.32	--	nc
T1139	2,448.68	2,448.53	2,448.78	--	nc
Y1139[3]	2,369.54	2,369.54	2,369.68	2,369.54	0
1RLB	--	--	2,270.80	--	nc
6RLB	--	--	2,280.05	2,279.99	nc
L68	2,282.45	2,282.22	2,282.08	2,282.15	.3
5RLB	--	--	2,274.21	2,274.21	nc
10GWM	--	2,327.43	2,327.29	--	nc
GWM11	--	2,283.10	2,282.98	--	nc
JUNCTION	--	2,375.58	2,375.65	--	nc
68LC	--	2,330.20	2,330.17	--	nc
4RLB	--	--	2,269.02	--	nc
38RS	--	2,315.27	2,315.13	--	nc
LS38[2]	2,284.96	--	2,283.66	--	1.3

[1]The elevation of this bench mark located on bedrock and determined during surveys by National Geodetic Survey in 1965 was held at 2,447.32 ft.

[2]Estimated on basis of 1989-91 surveys.

[3]The elevation of this bench mark located on bedrock and determined during surveys by U.S. Geological Survey in 1973 was held at 2,369.54 ft.

PWS-0193-0015

Table 2. Bench-mark elevations and difference between 1961 and 1989-91 surveys

[NGS, 1961: First or second order surveys by National Geodetic Survey. USGS, 1973: First or second order surveys by U.S. Geological Survey. USGS, 1989-91: Third order surveys by U.S. Geological Survey. --, no data]

Bench mark	Elevation, in feet above sea level			
	NGS 1961	USGS 1973	USGS 1989-91	Difference between 1961 and 1989-91
G1155	2,284.99	2,284.67	2,284.38	0.6
M1155	2,300.82	2,299.57	2,297.66	3.2
J1140[1]	2,282.54	--	2,282.50	0
K1140[1]	2,284.18	--	2,284.22	0
H1140[1,2]	2,325.06	--	2,325.06	0
G1140	2,285.15	2,285.01	2,285.00	.2
N1155	2,309.33	2,308.27	2,306.08	3.3
106-125	2,333.78	--	2,331.15	2.6
106-123	2,339.09	2,337.78	2,336.29	2.8
V747[1]	2,280.88	--	2,280.47	.4
R1140	2,306.89	2,306.70	2,306.68	.2
L1155	2,286.48	2,285.48	2,283.89	2.6
K1155	2,287.07	2,286.26	2,285.21	1.9
J1155	2,277.71	2,277.18	2,276.76	1
2MDC	[3]2,298.05	2,296.80	2,295.21	2.8
K487	2,313.88	--	2,313.54	.3
R488	2,337.79	2,337.69	2,337.66	.1
E1140	2,320.36	2,320.23	2,320.26	.1
29MDC	[3]2,295.77	2,295.75	2,295.66	.1
35MDC	[3]2,279.45	2,279.45	2,279.39	.1
Y1140	2,291.60	2,291.39	2,291.37	.2
S1140	2,309.22	2,309.02	2,309.01	.2
D1140	2,299.87	2,299.70	2,299.67	.2
P1140	2,286.23	--	2,286.05	.2

[1]Bench marks on same line surveyed in 1961 and 1990-91. The small discrepancies between 1961 and 1991 elevations are attributed to variations in leveling adjustments because the elevation of bench mark H1140 is held constant.
[2]Bench mark located on bedrock and assumed to be stable for surveys 1961-91.
[3]Values estimated from recent survey data.

A comparison of 1989-91 differential leveling and 1989 GPS survey results for selected bench marks is given in table 3. The median difference in elevation between the two methods is 0.09 ft. The mean elevation difference of about 0.10 ft indicates that the amount of land subsidence estimated using GPS data is accurate to the nearest ± 0.1 ft (tables 1 and 2).

All surveys made at the base in 1973 were based on the elevation of bench mark F1147, which was established north of Rosamond in 1961 (fig. 5). This bench mark is on an outcrop of a light-colored, indurated, tuffaceous rock of Tertiary age, at an elevation of 2,447.318 ft above sea level, (U.S. Department of Commerce, 1966). It is about 1.2 mi north of Rosamond on the west side of a dirt road that parallels State Highway 14. The stratified, pyroclastic rocks dip gently southwest and lie unconformably above pre-Tertiary quartz monzonite (Dibblee, 1963, p. 156-160) and below Miocene fanglomerate (Dibblee, 1958, p. 141; 1963, p. 187). There is no evidence of recent tectonic movement along any of the major or minor faults in the surrounding area (Dibblee, 1963), indicating that the bedrock at bench mark F1147 is stable. Other bench marks included in the vertical-control network on Edwards AFB that are considered to be on similar stable rock (bedrock) outcrops are Y1139, H1140, Grinell (triangulation station), and Buckhorn (fig. 4).

Table 3. Results of 1989-91 differential leveling surveys and 1989 Global Positioning System (GPS) surveys

Bench-mark pairs	Line length (miles)	Elevation difference, in feet above sea level		
		GPS surveys 1989	Differential leveling 1989-91	Summary difference (absolute value)
106-130 to 106-122 offset	6	20.866	21.020	0.154
H1155 offset to GWM2	7.9	26.406	26.340	.066
4MDC to M1155	2.8	34.514	34.577	.063
H1155 offset to M1155	4.4	21.944	21.906	.038
F1147 to U56	1.7	121.490	121.506	.016
3RLB to 1RLB	3.2	.951	1.093	.142
1RLB to 5RLB	3.6	3.412	3.417	.05
1RLB to 6RLB	3.4	9.252	9.260	.008
3RLB to 33MDC	3.1	6.923	6.847	.076
GWM2 to 3RLB	6.7	30.348	30.258	.09
GWM11 offset to 5RLB	.7	9.416	9.503	.087
106-122 offset to V1155	4	42.454	42.714	.260
V1155 to BUCKHORN	2.4	104.888	104.645	.243
L68 to 6RLB	.9	2.034 .	2.160	.126
Median				0.09
Mean				0.10

MAGNITUDE AND AREAL EXTENT OF LAND SUBSIDENCE

A comparison of the results of differential leveling surveys for 1961 and 1989-91 indicates the extent of land subsidence at Edwards AFB and at selected, nearby locations. The greatest amounts of subsidence at the base for 1961-91 are near the South Track well field (figs. 5 and 6) and near the southern border of the base. Land subsidence for 1961-91 ranged from about 0.2 ft in areas near the north end of Rogers Lake to 3.3 ft south of the lake. Subsidence along the east edge of Rogers Lake near the Astronautics well fields is about 0.9 ft (figs. 5 and 6). A general decline in ground-water levels of about 90 ft since 1947 (fig. 7) is associated with land subsidence on the base.

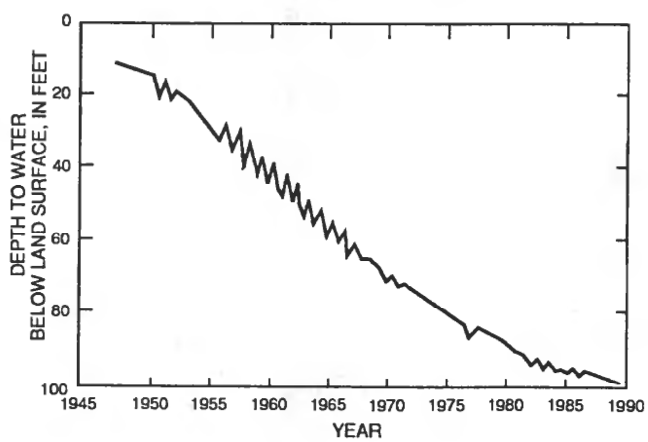


Figure 7. Ground-water-level decline, 1947-89, well 9N/10W-12R1S, South Base well field. Depth of well is about 250 feet.

Bench mark 33MDC (figs. 5 and 8), on the east side of Rogers Lake, shows an interesting subsidence phenomenon. When this bench mark was established in 1973, the brass cap and the top of the 6-inch diameter pipe were placed flush with the land surface. The brass cap presently is about 0.3 ft above the 6-inch diameter pipe, which is about 0.1 ft above the land surface. Wind erosion of the soil probably caused the 0.1 ft exposure of the 6-inch diameter pipe. The brass cap is 0.3 ft lower in elevation thanin 1973 on the basis of elevations determined from the regional vertical-control network surveyed in 1989-91 (table 1). The depth of the pipestem that supports the brass cap is unknown, but it is likely to be less than 20 ft. Therefore, there may be both shallow (depths less than 20 ft) and deep (depths greater than 20 ft) subsidence occurring at this site.

PWS-0193-0017

Figure 8. Bench mark 33MDC showing near-surface land subsidence that has caused exposure of the bench-mark stem. Bench mark, located east of Rogers Lake near Mercury Boulevard, was installed in 1973. Photographed April 1990.

Figure 9. Holly extensometer site, looking east. Extensometer is in large building in center. Observation wells are in small, round buildings. Land-surface elevation is 2,302 feet. Photographed August 1990.

EXTENSOMETER INSTALLATION

In May 1990, an extensometer was installed at the Holly well site (fig. 9) to measure the amount and rate of land subsidence near the South Track well field (fig. 5). This site was selected because bench marks M1155 and P1155, near the extensometer site, have subsided more than 3 ft since 1961 and represent the largest amount of subsidence documented to date on the base (fig. 6).

At the extensometer site, an 8- × 12-foot metal building houses the extensometer, and two small, round 36-inch diameter buildings (fig. 9) house the

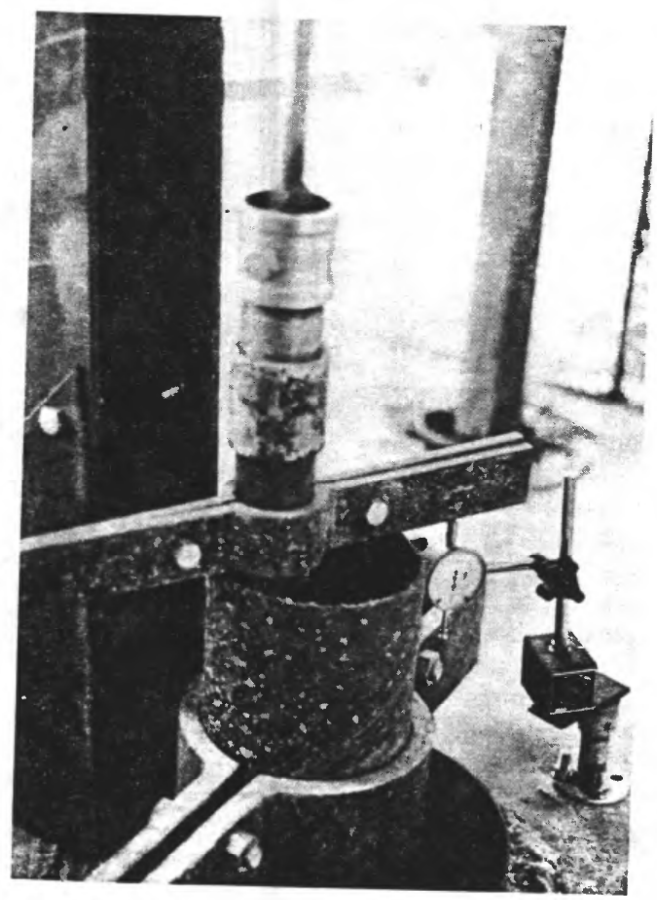


Figure 10. Holly extensometer. A 2-inch diameter pipe in center extends to a concrete anchor 840 feet below land surface. Dial indicator on right measures difference in distance between concrete floor (land surface) and horizontal bracket on pipe. Photographed May 1990.

PWS-0193-0018

nested observation wells that are used to measure water levels. The extensometer is a 10-inch diameter steel casing placed at land surface to protect a 6-inch diameter steel well casing that is 810 ft deep. Inside the 6-inch diameter casing and extending below land surface is a 2-inch diameter steel pipe embedded in concrete at a depth of about 840 ft. Granitic rock (possibly bedrock) at this site was 1,097 ft below land surface. The concrete anchor for the 2-inch diameter pipe is normally placed on bedrock or in coarse-grained strata several hundred feet below the level of ground-water pumping or strata that may be subject to subsidence. As the land surface subsides, the 2-inch diameter pipe will extend further above the land surface, and the amount and rate of land subsidence are then recorded using a data logger, drum recorder, and dial indicator (fig. 10).

Aquifer compaction at the Holly extensometer site between May 11, 1990, and October 1, 1991, was 0.078 ft (fig. 11). The rates of compaction shown on this figure, 1.88×10^{-4} ft/d prior to Julian day 259 (September 17, 1990), and 1.97×10^{-4} ft/d after Julian day 463 (April 12, 1991), indicate a continued rate of aquifer compaction that decreased only during the winter months of October 1990 through April 1991.

Water levels were measured at four wells located in two buildings near the Holly extensometer (fig. 9). One building houses one 2-inch diameter pipe placed to a 130 ft depth and two wells with 3-inch diameter pipes placed to depths of 470 and 645 ft. The second building houses a well that is 1,020 ft deep. Water

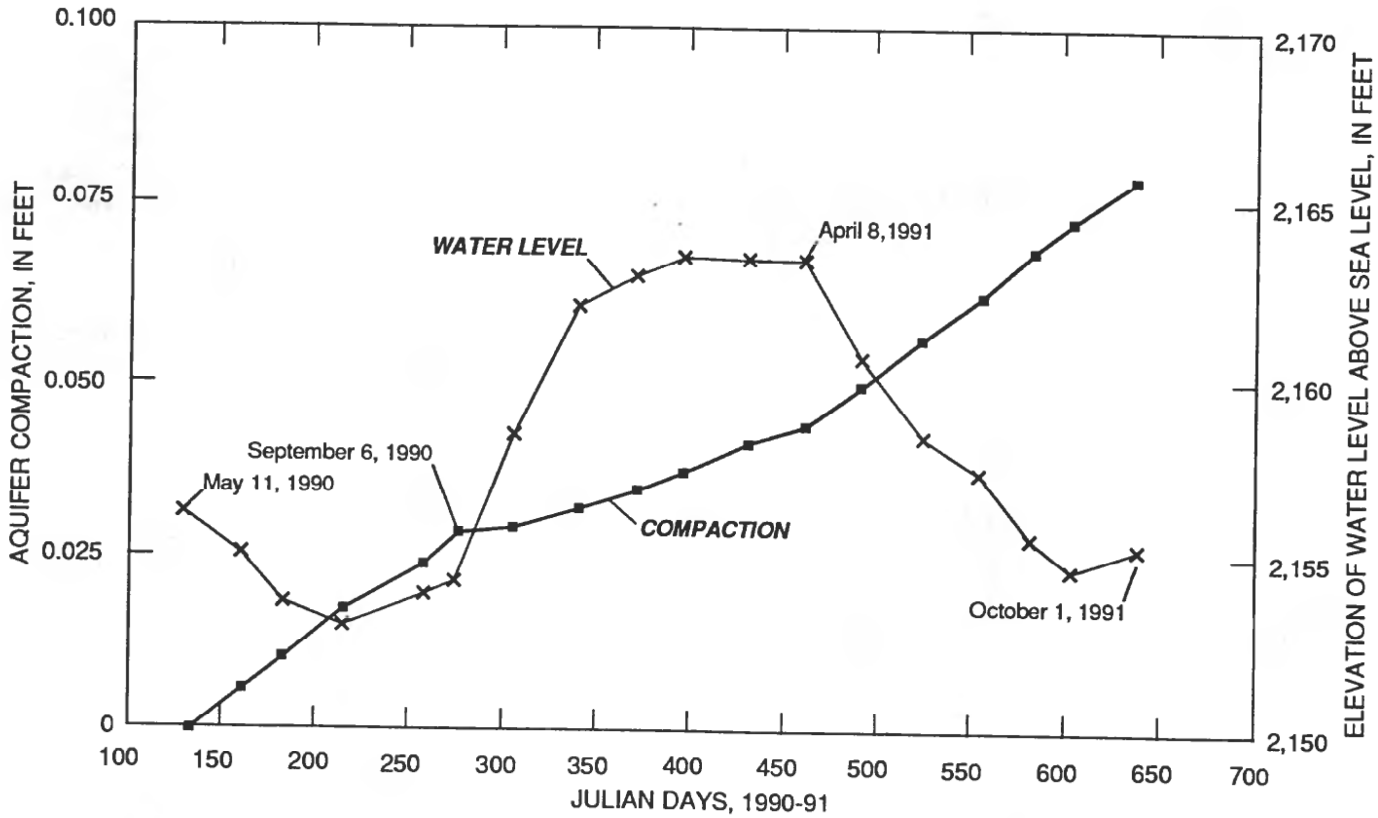


Figure 11. Aquifer compaction and water-level change between May 1990 and October 1991 at the Holly extensometer site.

PWS-0193-0019