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: U.S. Geological Survey Subsidence Interest Group Conference, Edwards Air Force Base, Antelope Valley, California, November 18-19, 1992: Abstracts and Summary; Open File Report 94-0532; 1995 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.

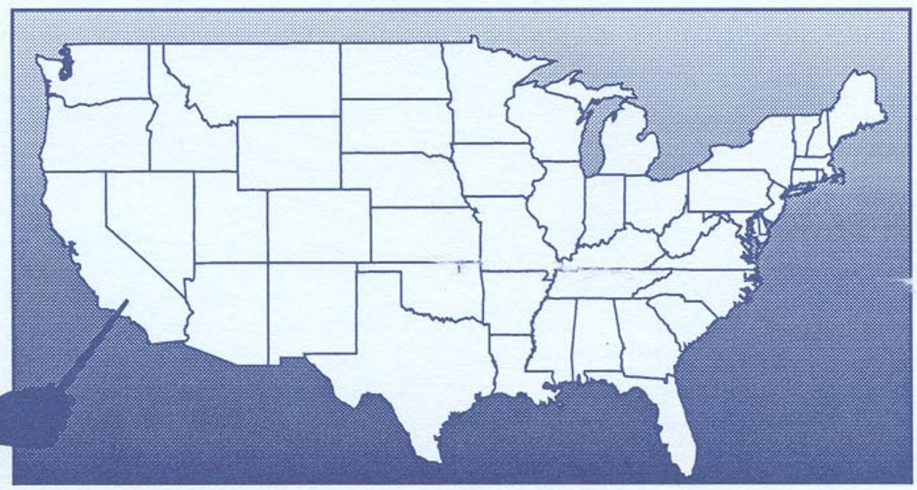
SIGNATURE: Jamie Wilson

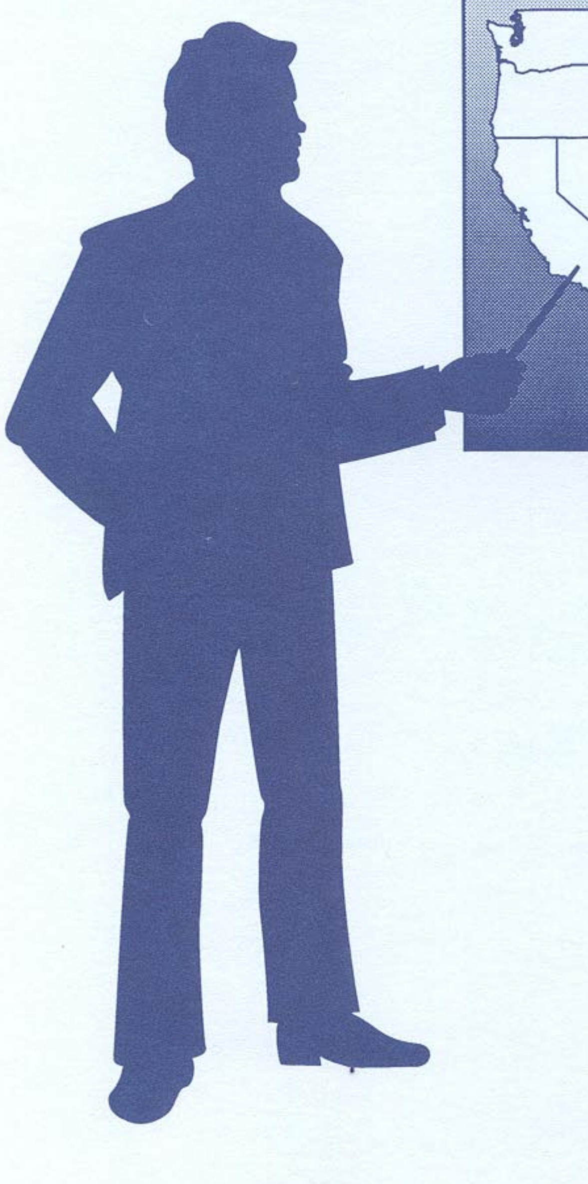
TITLE: Business Partner Specialist

OFFICE: United States Geological Survey

PWS-0196-0001

U.S. GEOLOGICAL SURVEY SUBSIDENCE INTEREST GROUP CONFERENCE, EDWARDS AIR FORCE BASE, ANTELOPE VALLEY, CALIFORNIA, NOVEMBER 18-19, 1992: ABSTRACTS AND SUMMARY





U.S. GEOLOGICAL SURVEY
Open-File Report 94-532

PWS-0196-0002

U.S. GEOLOGICAL SURVEY SUBSIDENCE INTEREST GROUP CONFERENCE, EDWARDS AIR FORCE BASE, ANTELOPE VALLEY, CALIFORNIA, NOVEMBER 18-19, 1992: ABSTRACTS AND SUMMARY

By Keith R. Prince, Devin L. Galloway, *and* Stanley A. Leake, editors

---

U.S. GEOLOGICAL SURVEY
OPEN-FILE REPORT 94-532

7210-26

Sacramento, California

1995

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

For sale by the
U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, MS 517
Denver Federal Center
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

PWS-0196-0004

CONTENTS

PWS-0196-0006

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	0.4047	hectare
acre	4,047	square meter
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot (acre-ft)	1,233	cubic meter
centimeter (cm)	0.3937	inch
centimeter per year (cm/yr)	0.3937	inch per year
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic meter (m^3)	35.31	cubic foot
cubic meter per day (m^3/d)	35.31	cubic foot per second
foot (ft)	0.3048	meter
foot per year (ft/yr)	0.3048	meter per year
gallon (gal)	3.785	liter
gallon per day (gal/d)	3.785	liter per day
gallon per minute (gal/min)	0.06308	liter per second
gram (g)	0.03527	ounce, avoirdupois
gram per cubic centimeter (g/cm^3)	0.6243	pound per cubic foot
inch (in.)	25.4	millimeter
kilometer (km)	0.6214	mile
kilometer per second (km/s)	0.6214	mile per second
kilopascal (kPa)	0.1450	pound per square inch
meter (m)	3.281	foot
mile (mi)	1.609	kilometer
milligrams per liter (mg/L)	1.0	parts per million
millimeter (mm)	0.03937	inch
millimeter per year (nn-n/yr)	0.03937	inch per year
million gallons (mGal)		
pound per square inch (lb/in^2)	6.895	kilopascal
square meter per day (m^2/d)	10.76	square foot per day
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
square kilometer (km^2)	0.3861	square mile
ton, short	0.9072	megagram

Temperature can be converted between degrees Celsius (°C) and degrees Fahrenheit (°F) by the following equation:

$$°F=1.8(°C)+32 \qquad °C=(°F-32)/l.8$$

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-0196-0007

SUMMARY OF TALKS, DISCUSSIONS, FIELD TRIP, AND OUTSTANDING ISSUES

Keith R. Prince (U.S. Geological Survey, Menlo Park, California)

Land subsidence, the loss of surface elevation as a result of the removal of subsurface support, affects every state in the United States. More than 17,000 mi^2 of land in the United States has been lowered by the various processes that produce land subsidence with annual costs from resulting flooding and structural damage that exceed $125 million. It is estimated that an additional $400 million is spent nationwide in attempts to control subsidence. Common causes of land subsidence include the removal of oil, gas, and water from underground reservoirs; dissolution of limestone aquifers (sinkholes); underground mining activities; drainage of organic soils; and hydrocompaction (the initial wetting of dry soils). Overdrafting of aquifers is the major cause of areally extensive land subsidence, and as ground-water pumping increases, land subsidence also will increase.

Land subsidence and its effects on engineering structures have been recognized for centuries, but it was not until this century that the processes that produce land subsidence were identified and understood. In 1928, while working with field data from a test of the Dakota Sandstone aquifer, O.E. Meinzer of the U.S. Geological Survey recognized the compressibility of aquifers. Around the same time, Karl Terzaghi, a soil scientist working at Harvard University, developed the one-dimensional consolidation theory that provided a quantitative means of predicting soil compaction resulting from the drainage of compressible soils. Thus, with the recognition of the compressibility of aquifers (Meinzer), and the development of a quantitative means of predicting soil compaction as a consequence of the reduction of intergranular pore pressure (Terzaghi), the theory of aquifer-system compaction was formed.

With the widespread availability of electric power in rural areas, and the advent of the deep turbine pump, ground-water withdrawals increased dramatically throughout the country in the 1940’s and 1950’s. Along with this unprecedented increase in pumpage, substantial amounts of land subsidence were observed in several areas of the United States, most notably in Arizona, California, and Texas. Beginning in 1955, under the direction of Joseph Poland, the Geological Survey began the “Mechanics of Aquifers Project,” which focused largely on the processes that resulted in land subsidence due to the withdrawal of ground water. This research team gained international renown as they advanced the scientific understanding of aquifer mechanics and land-subsidence theory. The results of field studies by members of this research group not only verified the validity of the application of Terzaghi’s consolidation theory to compressible aquifers, but they also provided definitions, methods of quantification, and confirmation of the interrelation among hydraulic head declines, aquifer-system compaction, and land subsidence. In addition to conducting pioneering research, this group also formed a “center of expertise,” providing a focal point within the Geological Survey for the dissemination of technology and scientific understanding in aquifer mechanics. However, when the “Mechanics of Aquifers Project” was phased out in 1984, the focal point for technology transfer no longer existed.

Interest among various state and local agencies in land subsidence has persisted, and the Geological Survey has continued to participate in a broad spectrum of cooperative and Federally funded projects in aquifer mechanics and land subsidence. These projects are designed to identify and monitor areas with the potential for land subsidence, to conduct basic research in the processes that control land subsidence and the development of earth fissures, as well as to develop new quantitative tools to predict aquifer-system deformation. In 1989 an ad hoc “Aquifer Mechanics and Subsidence Interest Group” (referred to herein as the “Subsidence Interest Group”) was formed to facilitate technology transfer and to provide a forum for the exchange of information and ideas among scientists actively working in subsidence and aquifer-mechanics-related projects. The Subsidence Interest Group is not focused solely on land subsidence resulting from ground-water withdrawals, although this is one of the primary areas of study for many of the group's members. Subsidence Interest Group members are also actively involved in studies of subsidence due to sinkhole collapse (karst), drainage of organic soils, geothermal development, and hydrocompaction. The group also is seeking to expand its expertise to include subsidence resulting from subsurface mining activities.

The first technical meeting of the Subsidence Interest Group was held at Phoenix, Arizona, in December 1989 and included formal presentations on the history of land subsidence studies as well as ongoing studies being done by the Geological Survey. As a result of this initial meeting, several new collaborative research efforts were begun. The second meeting of the group was held at Edwards Air Force Base, California, in November 1992, and included technical presentations of ongoing research and a field trip to view subsidence features and monitoring equipment installations in the surrounding Antelope Valley area. This report includes extended abstracts of the oral presentations summarizing the results of ongoing research that were given at that second meeting.

The report includes case studies of land subsidence and aquifer-system deformation resulting from karst processes, fluid withdrawal, and geothermal development. Several of the abstracts deal with various aspects of land subsidence and earth fissuring at Edwards Air Force Base that are resulting in extensive damage to runways used by military aircraft and the NASA Space Shuttle. Methods for monitoring land subsidence are described, including the application of two different techniques for using Global Positioning System technology for the rapid and accurate measurement of changes in land-surface altitude. Measurement techniques and theories describing the processes governing the formation of earth fissures are presented. Ongoing research into the development of numerical techniques for simulation and quantification of 3-dimensional aquifer-system deformation are also presented. Recently developed analytical and numerical techniques for the simulation of aquifer-system compaction due to fluid withdrawal are summarized.

The information presented in this report should help expand the scientific basis for management decisions to mitigate or control the effects of land subsidence. The papers describing the results of these studies provide an excellent cross section of ongoing research in aquifer mechanics and land subsidence and also form an assessment of the current technology and "state of the science." The analytical and interpretive methods described in this report will be useful to scientists involved in studies of ground-water hydraulics and aquifer-system deformation.

SUBSIDENCE INTEREST GROUP CONFERENCE AGENDA

Edwards Air Force Base, California

November 18–19, 1992

Wednesday - November 18th

8:00 AM	Opening remarks and introductions	Keith Prince, Menlo Park, CA
8:10	Welcome	Larry Plews, Edwards AFB, CA
8:20	Incidents and causes of land subsidence in the karst terrain of Florida	Craig Hutchinson, Tampa, FL
8:45	Subsidence caused by geothermal development near Mammoth Lakes, California	Christopher Farrar, Santa Rosa, CA
9:10	Land subsidence at Luke Air Force Base, Arizona	Herbert Schumann, Tempe, AZ
9:45	Break	
10:15	Land subsidence in El Paso	Charles Heywood, Albuquerque, NM
10:45	Preliminary look at land subsidence in the Ventura/Oxnard areas, California	Randall Hanson, San Diego, CA
11:00	Land subsidence associated with the San Jacino Fault, California	Douglas Morton, Riverside, CA
11:15	Static GPS surveys in land subsidence investigations in California	Marti Ikehara, Sacramento, CA
11:45	Lunch	NASA Cafeteria
1:00 PM	Kinematic GPS surveys in southern Arizona	Donald Pool, Tucson, AZ
1:30	Analysis of strain induced water-level fluctuations for estimates of aquifer elastic storage and hydraulic diffusivity	Devin Galloway, Sacramento, CA
2:00	Horizontal strain and tilt associated with water-level fluctuations—measurement techniques and results	Michael Carpenter, Tucson, AZ
2:45	Break	
3:15	Hydraulic forces associated with the generation of earth fissures at depth	Donald Helm, Las Vegas. NV
4:00	Simulation of three-dimensional granular movement	Thomas Burbey, Carson City, NV
4:45	Adjourn	

PWS-0196-0010

Thursday - November 19th

8:00 AM	Overview of methods of simulating land subsidence with “MODFLOW”	Stanley Leake, Tucson, AZ
8:45	Simulation of transient ground-water flow and land subsidence in Picacho Basin, Arizona	Donald Pool, Tucson, AZ
9:15	Break	
9:45	Antelope Valley projects	
	Introductions—	Devin Galloway, Sacramento, CA
	- Antelope Valley regional geology	Gary Dixon, Las Vegas, NV Wesley Ward, Flagstaff, AZ
	Land subsidence and related factors—	
	- Hydrogeology of Antelope Valley	Clark Londquist, Sacramento, CA
	- Measurement of land subsidence: The Edwards AFB and Antelope Valley networks	Marti Ikehara, Sacramento, CA
	- Measurements of land deformation: The shape of the subsidence surface and its relation to earth fissures, and erosional features	James Blodgett, Sacramento, CA
	Managing in the future—	
	- Antelope Valley: Land subsidence as a resource management objective	Steven Phillips, Sacramento, CA
	- Edwards Air Force Base: Land subsidence and the base comprehensive plan	Larry Plews, Edwards AFB, CA,
	Discussion—	
11:45	Lunch	NASA Cafeteria
Field Trip—	Edwards Air Force Base 1:30–5:30 PM	Francis Riley, Menlo Park, CA Gary Dixon, Las Vegas, NV Antelope Valley Studies Group, Sacramento, CA
1:30 PM	Convene tour: Hospital Ridge, Generals Quarters Overlook. Geologic and hydrologic boundary features, Mt. Mesa, San Gabriels, Tehachapis, the east Antelope structural basin, Antelope Valley Fault Zone and associated spring line, Graham Ranch Basin, South Track and South Base well fields, overview of subsidence affected areas.	
2:15	Holly site—one deep (840 ft) extensometer and four piezometers: counterweighted pipe extensometer with reference table, review compaction and water-level record.	

PWS-0196-0011

3:30	Fissure site—two shallow (<55 ft) extensometers and five piezometers: pipe extensometers with reference table, review compaction and water-level record; earth fissure; fissure monument array; water-level monitoring installation.	
4:45	Runway 17 (designated Space Shuttle runway) fissure zone: relation to inflection on land-surface elevation profile, and geologic structure—Antelope Valley Fault Zone at the El Mirage Fault.	
5:30	Dinner	Officers' Club
7:30	USGS Subsidence Interest Group meeting	Officers' Club
	Subsidence in People's Republic of China and interest in international cooperation	Stanley Leake, Tucson, AZ Donald Helm, Las Vegas, NV
	Recent effort by Western Region, Water Resources Division, USGS to brief USGS senior management on subsidence issues	Stanley Leake, Tucson, AZ Donald Helm, Las Vegas, NV
	Subsidence Interest Group position paper—Where do we go from here?	Open Discussion
	Subsidence Interest Group leadership—What is an appropriate form?	Open Discussion
10:00	Adjourn	

PWS-0196-0012

MUDBOILS IN THE TULLY VALLEY, ONONDAGA COUNTY, NEW YORK

William M. Kappel (U. S. Geological Survey, Ithaca, New York)

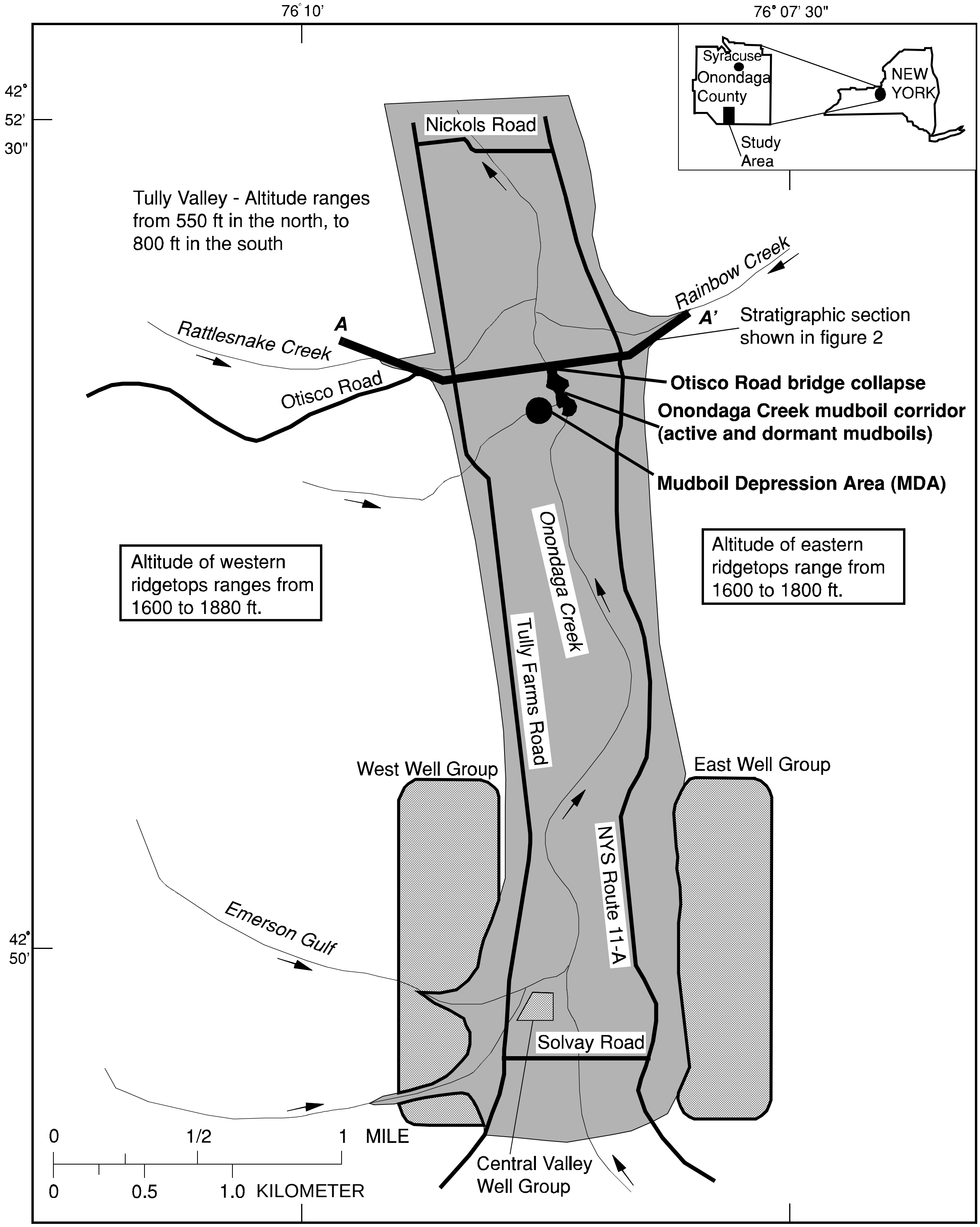
The discharge of turbid ground water and fine sand to the land surface in the Tully Valley, approximately 20 mi south of Syracuse, New York, has formed a series of mudboils (fig. 1). The volcano-like cone of a mudboil can be several inches to several feet high and from 1 ft to more than 30 ft in diameter. Where mudboil activity is persistent, the removal of sediment at depth has caused land subsidence. Depending on the depth of the source zone, individual mudboils discharge fresh or brackish ground water. The temperature of freshwater discharges ranges between 45 and 55 °F; the temperature of brackish water discharge is nearly constant at 51 °F. Mudboil activity may be natural or may be associated with a large solution salt-mining operation that began in the southern part of the valley in the late 1800’s and ceased in 1988. The mined salt beds range from 1,000 to 1,400 ft below land surface (fig. 2). The northern extent of the brining operation is 1 mi south of the mudboil area; the northern limit of its effect is unknown. Dissolution of the salt beds initially utilized injected surface water but since the late 1950’s dissolution has occurred only under natural conditions, involving ground-water infiltration to the salt beds from the surrounding fractured bedrock and possibly from the more permeable unconsolidated glacial deposits in the Tully Valley.

The earliest known mudboil in Tully Valley, reported in the Syracuse Post Standard on October 19, 1899, was apparently localized and short-lived. From 1899 to the 1970’s, the mudboils within the Onondaga Creek mudboil corridor (fig. 1) appeared and dissipated over a span of several weeks to a few months but had no long-term effect on the water quality of Onondaga Creek and Onondaga Lake, 20 mi downstream. Active mudboils became increasingly persistent during the mid-1970’s, causing turbid discharges that degraded the quality of Onondaga Creek. Before the mid-1980’s, relatively fresh ground water was discharged from what is now called the main ‘mudboil depression area’ (MDA), located 1,500 ft south of Otisco Road (fig. 1). Since then, however, the discharge has been more brackish, and land subsidence (locally as much as 15 ft) has progressed outward. In June 1991, a new mudboil appeared in Onondaga Creek just upstream of the Otisco Road bridge (fig. 1), and within 2 months the bridge collapsed. Subsidence around the 150-ft radius of this collapse area ranges from several inches at the perimeter to more than 5 ft at the bridge.

Flow measurements from the MDA during the 1992 water year indicate that there are seasonal variations in the amount of ground water discharged by the mudboils. Approximately 180 gal/min is discharged in the fall, compared to more than 360 gal/min in the spring. The mudboils, however, do not respond to individual storms. The average daily sediment concentration in the MDA discharge to Onondaga Creek for the 1992 water year is approximately 7,300 mg/L and the average sediment load (as clay, silt, and fine sand) is 35 tons per day.

The stratigraphic sequence of the glacial deposits (fig. 2) was defined through a shallow (<100 ft) drilling program. A source zone for water and mudboil sediments was identified beneath a sequence of silt- and clay-rich deposits. When the test wells penetrated this mudboil source zone, water, silt, and fine sand moved up the test-well casing, and water flowed at 3 to 5 gal/min at the land surface. When the casing was shut-in, the source zone had a measured hydraulic head about 600 ft above mean sea level, which is significantly above the surface of Onondaga Creek (540 to 545 ft) and the land surface of the MDA (550 to 555 ft).

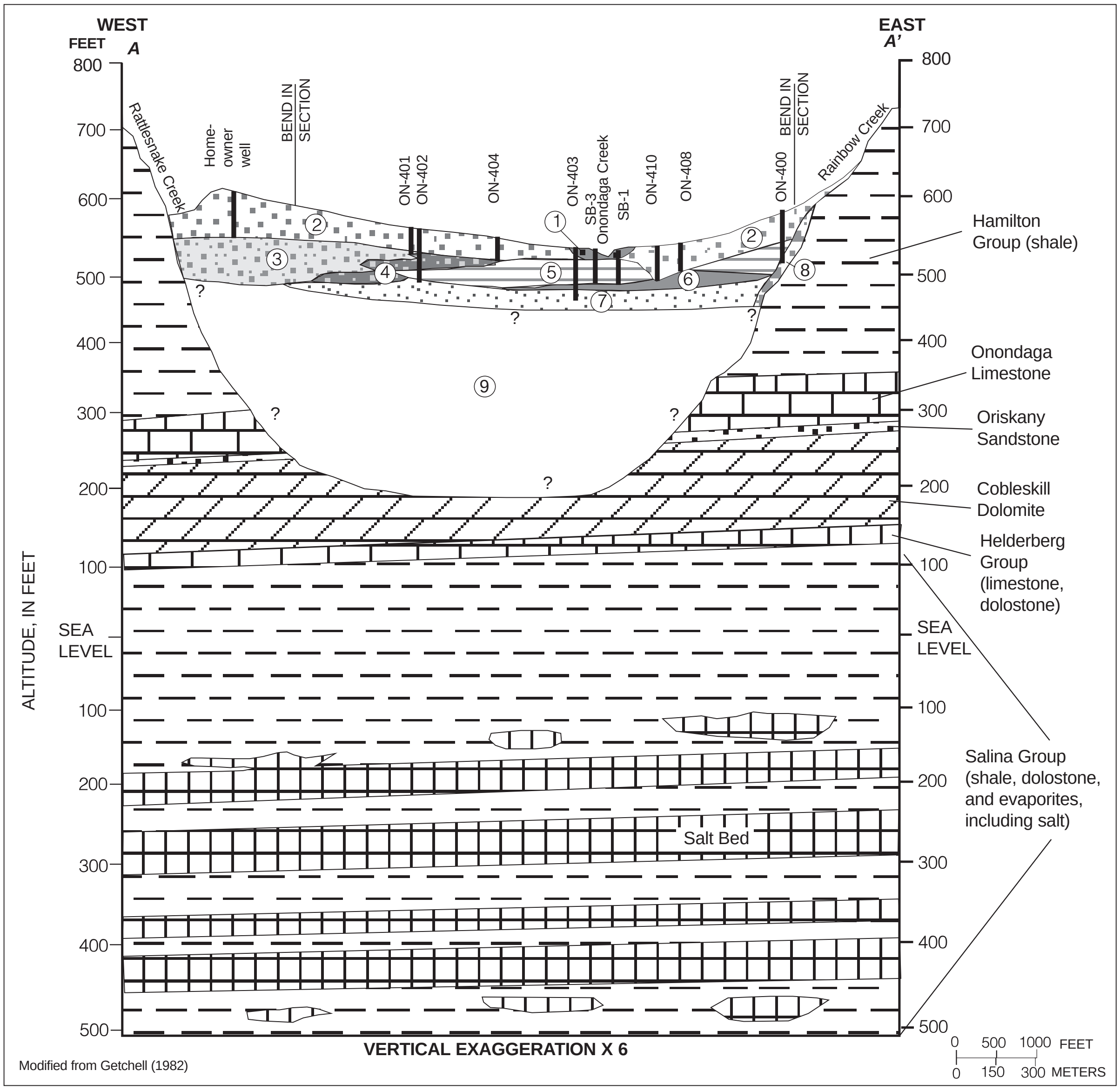
PWS-0196-0014



Base from Otisco Valley Quadrangle, 1955 1 : 24,000

Figure 1. Geographic features in the Tully Valley, Onondaga County, New York. Tully Valley is about 20 miles south of Syracuse, New York.

PWS-0196-0015



<u>ALLUVIAL DEPOSITS</u>

1. **FLOOD-PLAIN AND MUDBOIL DEPOSITS** -silt, sand, and gravel.

2. **FAN DEPOSITS -** mostly silty sand and gravel deposited by Rattlesnake and Rainbow Creeks.

<u>DELTAIC AND GLACIOLACUSTRINE DEPOSITS</u>

3. **LAMINATED SAND AND SOME SILT/CLAY -** mostly fine to medium sand interbedded with minor amounts of silt and clay.

4. **LAMINATED SAND AND SILT/CLAY -**very fine sand interbedded with silt/clay.

5. **LAMINATED CLAY WITH SOME SILT -** mostly clay interbedded with some thin, very fine sand layers: forms confining unit over liquifiable sand and silt (unit 7).

<u>DELTAIC AND GLACIOLACUSTRINE DEPOSITS cont'd</u>

6. **CLAY -** massive, forms confining unit over the liquifiable sand and silt described below.

7. **SAND AND SILT -** massive, mostly very fine to medium sand and silt with trace amounts of coarse to very coarse sand deposits under artesian conditions in low parts of the valley, commonly heaves-up into well casings and probably is the source of sediment issuing from the mudboils.

<u>OTHER GLACIAL DEPOSITS</u>

8. **TILL -** pebbles embedded in a clay matrix, may underlie entire glacial sequence in the valley.

9. **MIXED GLACIAL DEPOSITS -** Two sequences of lacustrine clay and silt grading to sand, gravel, and boulders with a possible till deposit along the bedrock surface.

Figure 2. Generalized section *A-A'* (location shown in figure 1) of the Tully Valley near Otisco Road, showing stratigraphy of the unconsolidated and bedrock units.

PWS-0196-0016

The causes of the mudboils are presently unknown because the hydrogeologic system is complex and incompletely understood. Factors that could be related to their origin, location, and water quality are:

1. Location*:* The mudboils are located near Onondaga Creek between the only two major side-wall stream valleys that enter the glaciated Tully Valley. As fine-grained materials were being deposited in front of the glacier, coarser materials were being deposited as foreset beds and/or fans from the two side valleys. The intersection of these two deposits may have created a zone of structural weakness, especially near the stream, where overburden stresses would be least due to the lower elevations of the streambed.

2. Hydrostatic pressure: The earliest reported mudboils were along Onondaga Creek, just downstream from two mills and a dam. The hydrostatic load placed on varved lacustrine deposits underlying the mill pond could have caused hydraulic piping through preexisting zones of weakness and created the first mudboil. Subsidence of the land surface as materials at depth were removed caused the process to become self-perpetuating.

3. Excavation and erosion: An oil pipeline, laid in the Tully Valley in 1931, crosses through the eastern end of the MDA. Even though mudboil activity and subsidence in this area were not reported until the 1950’s, the pipeline had to be lowered in August 1974, reportedly due to erosion caused by Hurricane Agnes (June 1972), the excavation temporarily reduced the overburden stress and coincided with increased mudboil activity.

4. Cessation of pumping: The cessation of the solution salt-mining field’s annual pumping of approximately 1 billion gal of brine in the late 1980’s caused the hydraulic head in the deep sand and gravel zone to increase by 70 ft or more, and this increased head coincided with the onset of increased mudboil activity and changes in the quality of water discharged from the MDA.

Subsidence of the land surface in the Tully Valley has occurred over the past 100 years, but the causes of this subsidence are varied. In the brine fields, uncontrolled solution mining of the deep salt beds has resulted in the collapse of large unsupported spans of rock materials immediately above the salt (Fernandez, 1991). In some cases the subsidence is gradual and occurs over a large area (tens of acres) as the upper bedrock units sag into the lower collapse area. In other cases the subsidence is confined to a small area (hundreds of square feet) due to the development of a “chimney” through the rock formations above the collapse area, which creates a sinkhole at the land surface (Fernandez, 1991).

Along Onondaga Creek and in the main MDA, land-surface subsidence is related to the discharge of ground water and fine-grained materials from the subsurface to the land surface where stream erosion moves the discharged mudboil sediments downstream. Continued discharge of subsurface materials and subsequent removal leads to land subsidence (see Helm abstract for discussion of related physical mechanisms in the formation of earth fissures). This process is gradual but perceptible, as noted in the collapse of the Otisco Road bridge.

A third type of subsidence is suspected but is currently undocumented—subsidence due to the compaction of fine-grained materials resulting from the aggressive pumping of ground water during the last 20 years of solution mining in the Tully Valley brine fields. The cessation of pumping resulted in a 70- to 100-ft recovery of water levels in the deep sand and gravel and probably brought this type of subsidence to a halt. Although the following information is circumstantial, it may indicate that this form of subsidence has occurred in the Tully Valley:

1. Measured datum changes: Subsidence of 1 to 2.5 ft at several locations on the floor of Tully Valley outside of the solution-mined areas has been measured at several temporary bench marks established by the brine-mining company (Mr. Jim Tyler, Allied Corporation, oral commun., 1992).

PWS-0196-0017

2. Changes in penetration rates: Decreases in drilling penetration rates at the base of the massive clay unit (unit 6, fig. 2) that overlies the sand and silt unit (unit 7, fig. 2) were noted during the shallow drilling program. Split-spoon samples collected from the middle part of the massive clay unit were advanced with the weight of the drill rods. The lower part of the massive clay unit required increasing down-pressure (as high as 450 lb/in^2) to collect several split-spoon samples.

3. Structural damage: Large-building foundations are reported to have separated, cracked, or subsided in all parts of the Tully Valley, both in and outside of the solution mining area.

Study of the Tully Valley mudboils will continue through 1993. Subsidence will be monitored at the main MDA to determine if any planned remedial actions will affect rates of subsidence. A deep well will be drilled to determine if there is a collapse feature in the bedrock beneath the MDA or if the saltbeds have been solutioned-out in this area. Ground-water samples from selected water-bearing zones in the bedrock, the basal sand and gravel unit, and the shallow mudboil source zone will be collected and compared with samples collected from fresh and brackish water mudboils to determine possible source zone(s) feeding the mudboils.

INCIDENTS AND CAUSES OF LAND SUBSIDENCE IN THE KARST OF FLORIDA

Craig B. Hutchinson (U.S. Geological Survey, Tampa, Florida)

Land subsidence has damaged at least 500 homes in Pinellas County (fig. 1) since 1990 according to the county property appraiser. Land subsidence has been attributed to compaction—natural compaction, liquefaction (see Kappel abstract), hydrocompaction, withdrawal of subsurface fluids (for example, see Hanson, Farrar and others, and Pool #1 abstracts); tectonic deformation (see Farrar and others, Morton, Ward and others abstracts); drainage of organic soils; and collapse into subsurface voids—mining and sinkholes (National Research Council, 1991). The Florida Sinkhole Research Institute conservatively estimates that sinkholes alone cause on the order of $10 million in damage each year in the State (Beck and Sayed, 1991). Geotechnical engineers estimate that about 20 percent of the subsidence problems in Florida are caused by sinkholes.

The carbonate rocks that underlie the Florida peninsula to depths of several thousand feet are susceptible to chemical solution by mildly acidic water that percolates through the soil as natural recharge. The development of karst can occur as water acidified by dissolution of carbon dioxide in the soil zone moves down vertical fractures and solution pipes, dissolving limestone all along the way to the water table. Upon reaching the water table, the still slightly corrosive water moves down gradient. Thus, limestone dissolution continues in a thin, nearly horizontal zone just below the water table. As the water table rises and falls, a complex horizontal system of interconnected caves and porous zones is formed. Eventually, the flowing ground water may return to the surface at a lower elevation through a system of springs. By then, the acid in the water has been neutralized, and the spring water is carrying all the lime it can dissolve. The natural rate of denudation of Florida limestone is estimated to be about 1 ft in 5,000 or 6,000 years. Pumping induces recharge and may artificially speed up the rate of denudation to 1 ft in 1,700 years in local areas (Sinclair, 1982).

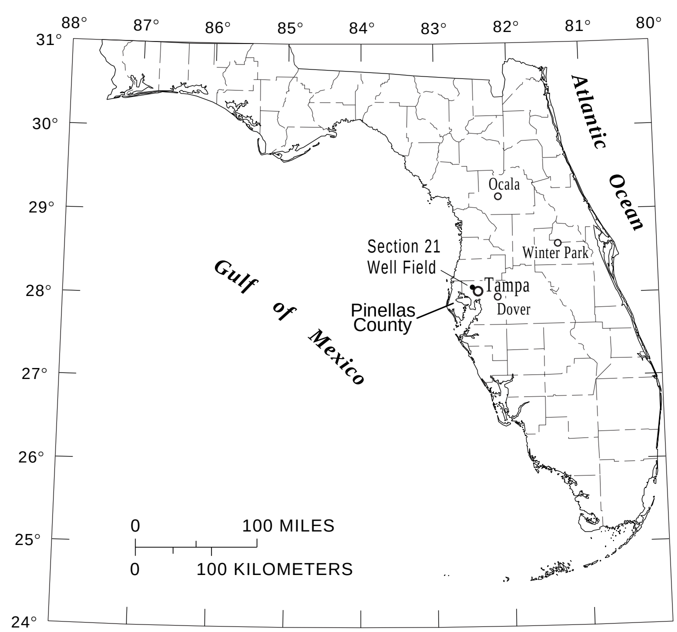


Figure 1. Locations of sinkhole study sites in Florida.

PWS-0196-0019

Sinkhole collapse can be triggered by sudden changes in ground-water levels, especially where the limestone aquifer is confined and under artesian pressure. An increase in the pumping rate of 3 million gal/d at the Section 21 well field near Tampa in April 1964 resulted in the formation of 64 new sinkholes within a 1-month period (Beck and Sinclair, 1986). Apparently, the sudden decline in artesian pressure triggered the collapse of cavities whose size had already become critical with respect to their bearing strength and the weight of the overlying overburden. Heavy rains also can trigger sinkholes in a similar way by raising the water table and thus the weight of the overburden with respect to the bearing strength of the limestone. Such an event occurred near Ocala in April 1992 when 12 in. of rain fell within an 8-hour period, triggering the formation of about 200 sinkholes. The effects of raising the water table and lowering the artesian pressure were combined in January 1977 near Dover when strawberry farmers protected their crops from freezing by irrigating with warm ground water. The artesian level of the limestone aquifer declined as much as 60 ft (pressure expressed as equivalent height of water) overnight and the water table rose a few feet, which resulted in reports of 22 new sinkholes.

The most dramatic example of sinkhole activity and damage in the history of the United States was the formation of the huge Winter Park sinkhole in May 1981. At the site, relatively loose sand forms a surficial aquifer about 60 ft thick, and an underlying clay forms an intermediate confining unit about 100 ft thick, above limestone that occurs about 160 ft below land surface. The water table is about 10 ft below land surface and the artesian level of the limestone aquifer is about 110 ft above sea level or about 50 ft below land surface. A cone-shaped sinkhole 40 ft in diameter and 20 ft deep appeared at about 8 p.m. on May 8 and slowly enlarged overnight to a diameter of 80 ft. Between 10 a.m. and noon on May 9, the sinkhole rapidly expanded to 300 ft in diameter and deepened to 110 ft. This sudden increase in activity probably resulted from the complete collapse of the roof of a huge cavern. During the rapid expansion phase, a house, three automobiles, and a municipal swimming pool were funneled into the sinkhole. The funneling of sand was so rapid that, apparently, the turbidity greatly increased the density of water in the sinkhole pool. The water level in the sinkhole formed a pool 10 ft in diameter and 50 ft below the artesian level of the limestone aquifer. The funnel tube was later measured to be 60 ft in diameter. Subtraction of the 10-ft pool indicates that a 25-ft thick ring of sand was flowing downward through the annulus between the edge of the pool and the cylindrical funnel tube. By May 10, the pond level coincided with the artesian level of the limestone aquifer where it remained for 2 weeks despite the water flowing in from the sand aquifer above. Over the next 4 months, sediment gradually plugged the erosion pipe to form a lake 300 ft in diameter. The natural lake resembles thousands of circular sinkhole lakes that dot the landscape of Florida.

A set of fifty-six 35-mm slides that relate to land subsidence in Florida was prepared for presentation at the U.S. Geological Survey Subsidence Interest Group Conference. Many of the slides were provided by Dr. Frank Kujawa of the University of Central Florida and by Dr. Barry Beck of the Florida Sinkhole Research Institute. The slides and accompanying text are available at the U.S. Geological Survey office in Tampa, Florida.

MONITORING AQUIFER COMPACTION AND LAND SUBSIDENCE DUE TO GROUND-WATER WITHDRAWAL IN THE EL PASO, TEXAS–JUAREZ, CHIHUAHUA, AREA.

Charles E. Heywood (U.S. Geological Survey, Albuquerque, New Mexico)

The two-million inhabitants of El Paso, Texas, and Juarez, Chihuahua, create a large demand for water in an arid environment. Much of this demand, about 195,000 acre-ft in 1989, is supplied by ground-water pumpage from the southern Hueco Bolson. The trend of population growth in this area is reflected by a trend in increased ground-water withdrawal, which is expected to continue into the next century.

Land subsidence is one consequence of ground-water withdrawal. Land and Armstrong (1985) reported up to 0.41 ft of land subsidence that occurred between 1967 and 1984 adjacent to the Rio Grande river in El Paso. In 1984, the historic water-level decline in the underlying Hueco Bolson aquifer was about 100 ft in the region of maximum measured subsidence (near Ascarate Lake) and about 150 ft under downtown El Paso. The minor subsidence associated with this water-level decline suggests that preconsolidation stress had not been exceeded by 1984, and compaction was in the elastic range.

The Sierra de Juarez and Franklin Mountains separate the southeast Mesilla Basin from the southern Hueco Bolson (fig. 1). The present Rio Grande flows from the Mesilla Valley into the Hueco Bolson at The Narrows, a topographic low at the southern end of the Franklin Mountains. Until the mid-Pleistocene, however, the ancestral Rio Grande flowed down the east side of the Franklin Mountains, and Bolson deposits aggraded to an elevation equivalent to the surface of the mesa bordering the present Rio Grande Valley. Approximately 0.6 million years ago, the Rio Grande breached the divide at The Narrows and eroded the Rio Grande Valley (John Hawley, New Mexico Bureau of Mines and Mineral Resources, oral commun., 1992). The Rio Grande has since deposited 100 to 200 ft of late Pleistocene and Holocene fluvial sediments in the Rio Grande Valley. The difference between the present elevations in the Rio Grande Valley and bordering mesa areas is typically between 240 and 320 ft and is representative of the net overburden removed by this cycle of erosion and re-aggradation. The resulting change in effective stress can be estimated using the Terzaghi (1925) relation by assuming an average grain density, porosity, and a water-level decline equal to the depth of sediments removed. For an average grain density of 2.7 g/cm^3 and an average porosity of 30 percent, an equivalent increase in effective stress would occur with a freshwater hydraulic head decline of about 1.2 times the thickness of eroded overburden. This decline (between 290 and 380 ft) from predevelopment heads is an estimate of preconsolidation stress expressed as a change in water level under confined aquifer conditions. Because freshwater supplies are limited under the Rio Grande Valley, this degree of consolidation suggests that compaction of the Bolson sediments under the Rio Grande Valley may remain in the elastic range for quite some time. The preconsolidation stress threshold for overlying late Pleistocene or Holocene fluvial sediments and Bolson sediments outside the Rio Grande Valley may be significantly lower as it is for analogous sediments elsewhere (Holzer, 1981).

Recognizing the need to quantify the mechanical response of the aquifer to various anthropogenic stresses in the El Paso–Juarez area, the U. S. Geological Survey (USGS), in cooperation with the National Geodetic Survey and the U. S. Section of the International Boundary and Water Commission, began a subsidence monitoring program in 1992. Conventional leveling determined bench-mark elevations to first order, first class accuracy from the Franklin Mountains to the Hueco Mountains, and southeast adjacent to the Rio Grande. The Global Positioning System (GPS) will be used to periodically monitor elevation changes at bench marks along these lines in addition to sites in Mexico (see Ikehara #1, #2, and Pool #1 abstracts for GPS applications in land subsidence investigations).

PWS-0196-0021

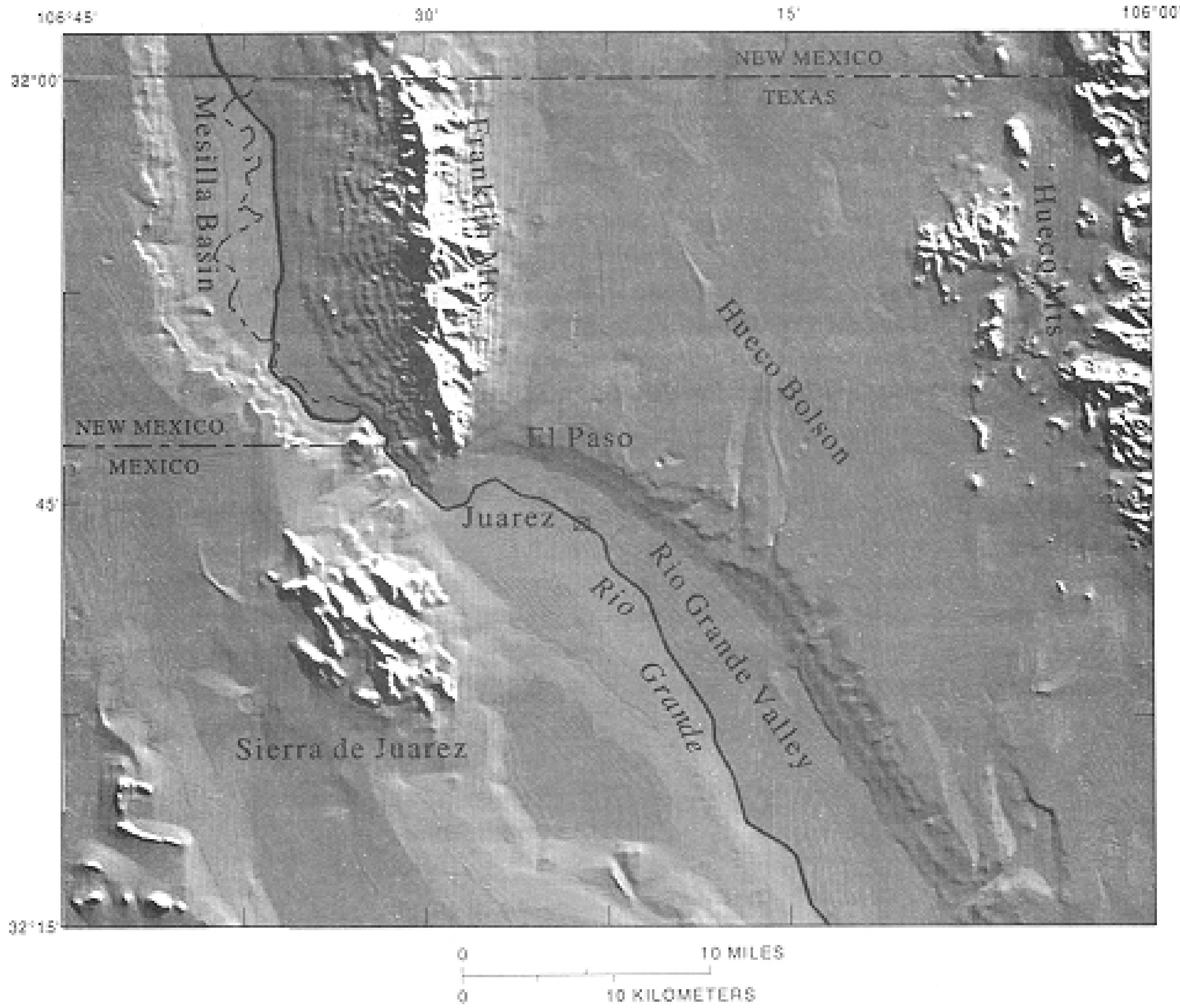


Figure 1. Shaded relief map of southern Hueco Bolson showing extensometer site at 31°44′35″N, 106°23′57″ W.

The rate of ground-water drawdown accelerated after a major reach of the Rio Grande was lined through El Paso in 1968 (White, 1983). The planned reconstruction and extension of the American canal through southeastern El Paso will decrease leakage from canals and an adjacent unlined reach of the Rio Grande, both of which are components of recharge to the underlying aquifer system. In order to differentiate future compaction in the shallow brackish zone under this reach of the Rio Grande from compaction in the deeper freshwater zone being pumped by the cities of El Paso and Juarez, dual extensometers were installed adjacent to this reach of the river. Because compaction magnitudes are likely to be small at this location and the data will be valuable to infer aquifer storage properties (see Galloway abstract for related discussions), the extensometer installations were designed to achieve maximum sensitivity. The deleterious effects of down-hole friction between the 2-in. extensometer pipe and 6-in. outer casing were minimized by drilling straight holes (deviation less than one degree) and chamfering extensometer pipe couplings. Effects of skin friction between the geologic formation and outer casing were minimized by sealing with a low-friction low-solid bentonite grout. Reverse pile effects were minimized by installing multiple slip joints to accommodate outer casing strain.

Both the USGS and a commercial logging company ran complete suites of borehole geophysical logs to a depth of 1,125 ft. The USGS long and short normal resistivity logs reproduced in figure 2 depict the sand and clay interbeds within the aquifer system. Two sets of three nested piezometers were installed to

PWS-0196-0022

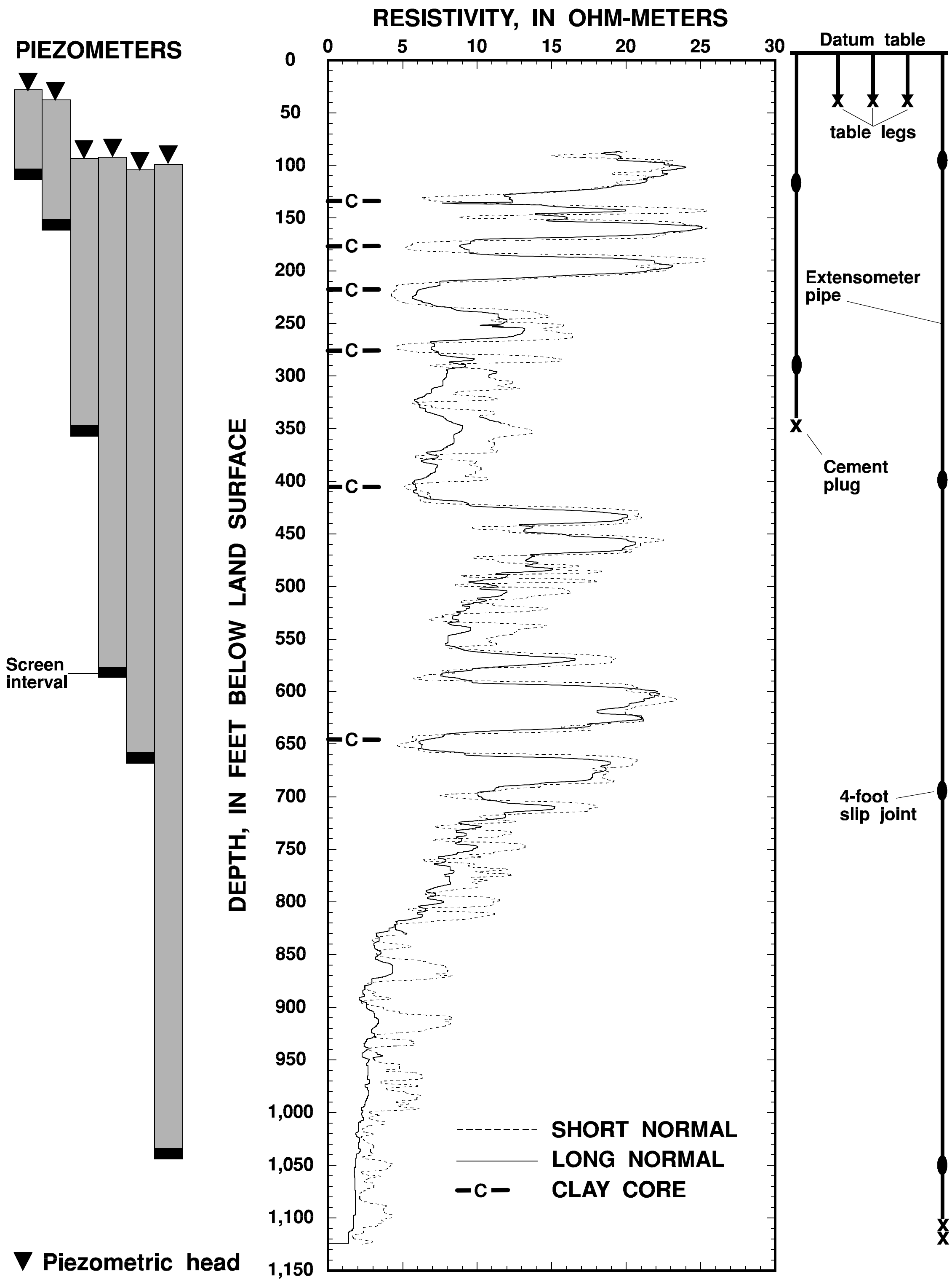


Figure 2. Hydrogeologic summary of extensometer site at the border of El Paso, Texas, and Juarez, Chihuahua.

PWS-0196-0023

monitor pore pressure in sandy zones at various depths. A steep downward hydraulic-head gradient is evident across multiple clay interbeds in the brackish zone down to 360 ft. Hydraulic head is lowest in the regional freshwater-producing zone from 350 to 700 ft. The increasingly saline conditions below 720 ft are reflected by decreasing electrical resistivity. The abundance of low permeability clay found below 1,068 ft suggests that significant pore pressure declines probably will not migrate below the base of the deep extensometer at 1,125 ft.

Clay samples 4 in. in diameter and 2 ft long were obtained from six major clay interbeds (fig. 2). X-ray analyses of these samples will determine their mineralogical constituents, and laboratory consolidation testing will yield measurements of elastic and inelastic compressibility, preconsolidation stress, and permeability. These point measurements will be compared to determinations made from the piezometer and extensometer records. Estimates of regional elastic and inelastic compressibilities (see Galloway abstract for related discussions), preconsolidation stresses, and permeabilities, in addition to the leveling data, will be used to refine the predictions of an evolving numerical ground-water flow and subsidence model (for example, see Burbey and Leake abstracts).

LAND SUBSIDENCE AND EARTH-FISSURE HAZARDS NEAR LUKE AIR FORCE BASE, ARIZONA

Herbert H. Schumann (U.S. Geological Survey, Tempe, Arizona)

Land subsidence and earth-fissure hazards near Luke Air Force Base are being investigated by the U.S. Geological Survey in cooperation with the U.S. Air Force. The main objectives of the investigation include the evaluation of land subsidence and earth-fissure hazards and the characterization of the surface- and subsurface-hydrogeologic conditions that may control the movement of contaminants toward and through the alluvial-aquifer system on and near the base. (See Ward and others, and Blodgett abstracts, for similar studies at Edwards Air Force Base). Differential land subsidence and resultant earth fissures have damaged buildings, roads, railroads, water wells, irrigation canals, and flood-control structures on or near the base, which is about 20 mi west of Phoenix, Arizona (fig. 1).

Large-scale pumping of ground water, mainly to irrigate crops in the surrounding area, has caused aquifer hydraulic heads measured in wells to decline more than 300 ft throughout much of the area. Ground-water depletion has caused the aquifer materials to compact and by 1991 had resulted in as much as 18 ft of land subsidence (fig 2). In August 1992, a Global Positioning System (GPS) satellite survey measured more than 17 ft of land subsidence northwest of the base (fig. 3). (See Ikehara #1, #2, and Pool #2 abstracts for GPS applications in land-subsidence investigations). Areas of maximum land subsidence correspond to areas of maximum hydraulic-head decline within the alluvial-aquifer system.

Large tensional breaks in the alluvial sediments, locally known as earth cracks or earth fissures, are caused by differential land subsidence. (See Haneberg and Helm abstracts for other possible mechanisms of earth-fissure formation). Earth-fissure zones as much as 2 mi long occur on the periphery of the areas of maximum land subsidence on three sides of the base (fig. 2). The earth fissures act as drains and are capable of capturing large volumes of surface runoff. When the fissures capture surface flows, the fissures enlarge by rapid erosion of the sides, by slumping, and by piping along the trend of the fissures. Such erosion can produce open fissure gullies as much as 15 ft deep and 30 to 40 ft wide in local areas. However, the fissures extend to depths far below the bottom of the fissure gullies and thus can provide vertical conduits for rapid downward movement of contaminants toward the water table. Part of the surface drainage from the south side of the base is captured by existing earth fissures.

The flood hazard on the base has been adversely affected by land subsidence. The gradient, or slope, of the Dysart Drain, which is a major flood-control channel along the north side of the base, has been reversed by differential land subsidence, and the carrying capacity of the drain and other flood-control structures has been greatly reduced (fig. 2). On September 20, 1992, a high-intensity storm produced about 4 in. of rain immediately north of the base and resulted in extensive flooding on the base. Floodwater overtopped the Dysart Drain and spilled onto the runways, into the aircraft parking areas, and into the base-housing area. The flooding closed the base for 3 days, inundated more than 100 homes, and generally disrupted base operations. Preliminary estimates of flood damage exceed $3 million.

Urbanization, together with commercial and industrial development, has occurred near the base in recent years. Any leakage of contaminants from the base into the nearby river channels or into the underlying body of ground water could affect the water resources of the area.

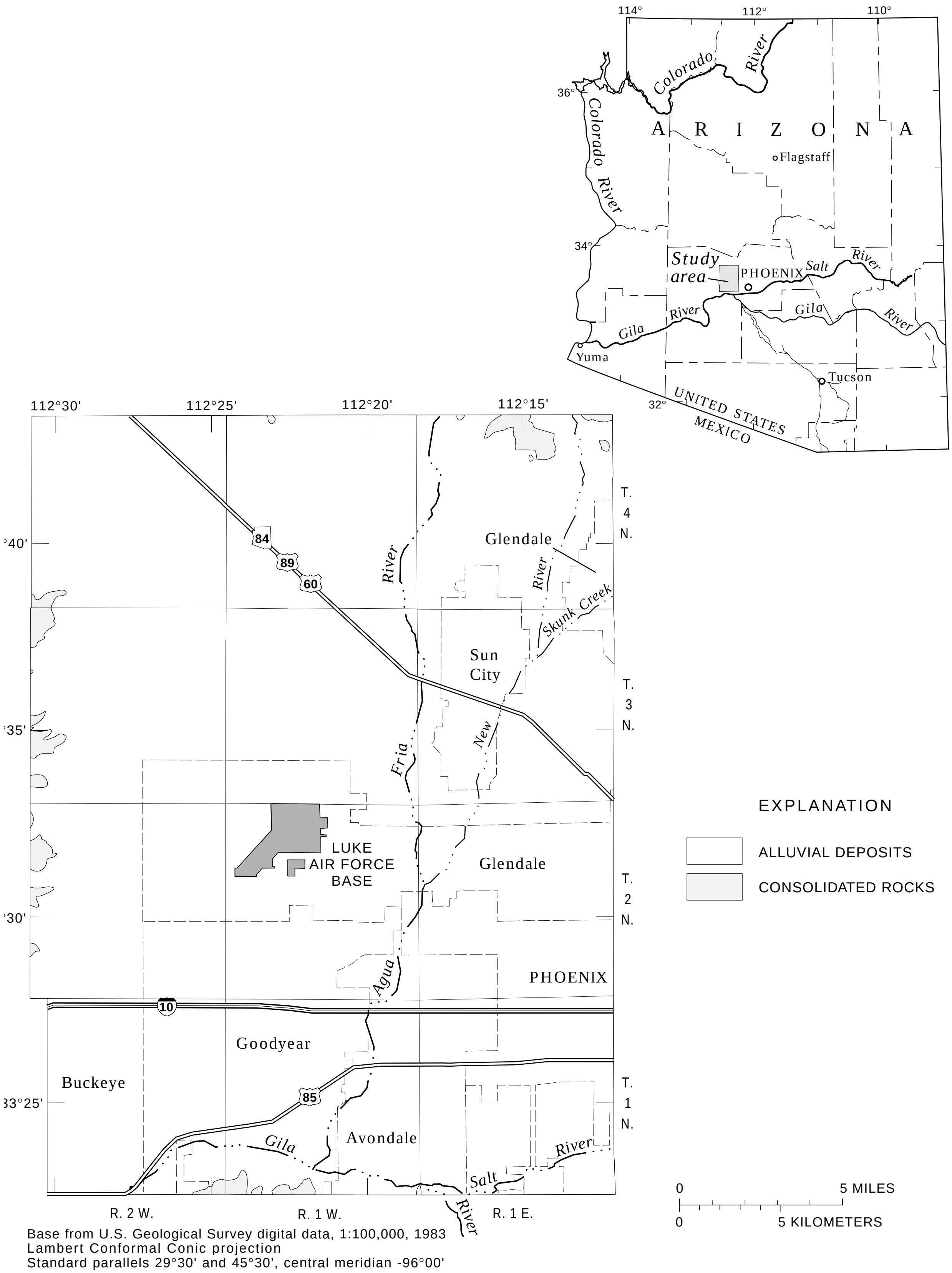


Figure 1. Location of Luke Air Force Base.

PWS-0196-0026

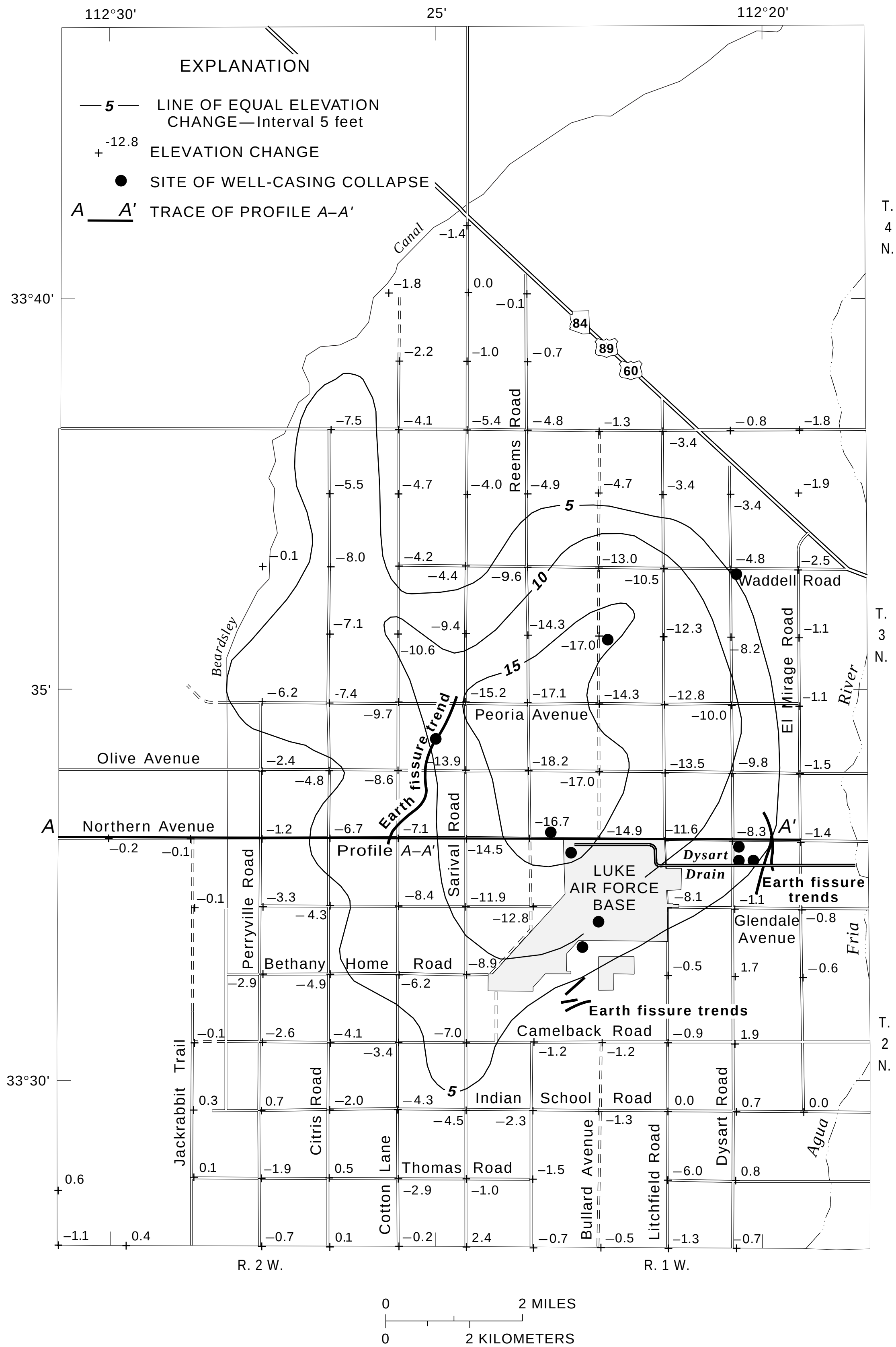


Figure 2. Land subsidence in part of the western Salt River Valley, 1957–1991.

PWS-0196-0027

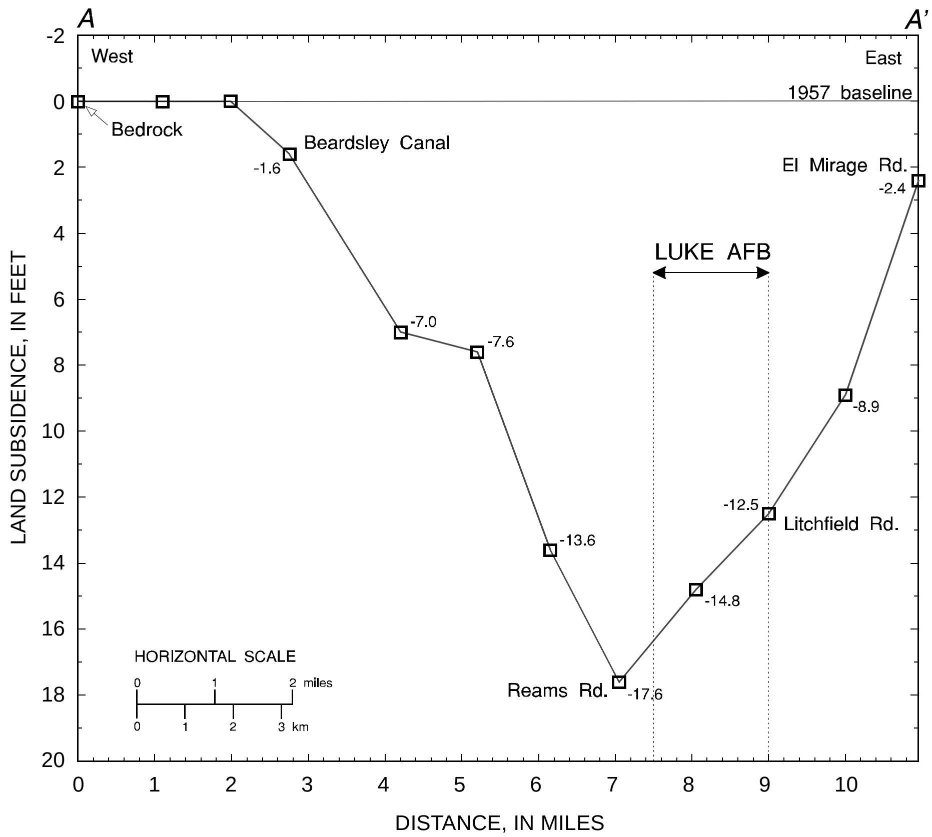


Figure 3. Profile of land subsidence, 1992, along Northern Avenue in the western Salt River Valley, Arizona.

PWS-0196-0028

SIMULATION OF TRANSIENT GROUND-WATER FLOW AND LAND SUBSIDENCE IN THE PICACHO BASIN, CENTRAL ARIZONA

Donald R. Pool (U.S. Geological Survey, Tucson, Arizona)

A numerical model of ground-water flow and land subsidence in a southwest alluvial basin was constructed using the modular finite-difference ground-water flow model (MODFLOW) by McDonald and Harbaugh (1988) to define parameters important to the simulation of land subsidence in alluvial basins and to evaluate the significance of aquifer-system compaction on regional ground-water flow (see Leake abstract for discussion of MODFLOW and the simulation of land subsidence). The Picacho Basin of south-central Arizona was studied because of the magnitude of ground-water pumping stresses and compaction and the availability of compaction and land-subsidence data (see Carpenter abstract for discussion of earth fissures in the Picacho Basin). Simulations included predevelopment conditions in 1887 and transient-flow conditions from 1887 to 1985. The transient-flow conditions are characterized by ground-water withdrawals greatly in excess of natural recharge, storage depletion, hydraulic-head declines of more than 100 m, and land subsidence of as much as 4.5 m.

The compressible part of the aquifer system includes the upper 1,000 m of alluvial deposits that are characterized by interbedded coarse-grained and fine-grained sediments on the basin margin and fine-grained sediments in the basin center (fig. 1). The middle confining bed separates the aquifer system into upper and lower aquifers. This confining bed consists of a thick sequence of fine-grained sediments that include several hundred meters of compressible sediments overlying as much as 2,000 m of relatively incompressible sediments. The difference in compressibility between the upper and lower sediments is inferred from a significant difference in physical properties. Compressible sediments are of low density, 1.9 to 2.2 g/cm^3; high porosity, 0.47 to 0.24 percent; and low seismic velocity, 2.2 to 2.5 km^2. Relatively incompressible sediments are of higher density, 2.2 to 2.5 g/cm^3; lower porosity, less than 0.24 percent; and higher seismic velocities, 2.5 to 4.6 km/s.

Fine-grained beds of various thickness and areal extent are the primary compressible sediments. The occurrence and thickness of individual fine-grained beds increase with depth and from the basin margin toward the basin center where individual beds merge into the middle confining bed. Rates of pore drainage and compaction in compressible fine-grained beds are influenced by bed thickness. One-dimensional simulation of compaction at an extensometer (Epstein, 1987) indicates that drainage of pores in beds that are less than 20 m thick requires less than a few years. Drainage of thicker beds may require decades.

Storage depletion has occurred through dewatering of pores in coarse-grained beds and reduction in pore volume in fine-grained beds. Early pumping was relatively shallow and storage loss occurred primarily through drainage of pore spaces at the water table. Many shallow coarse-grained beds were dewatered as water levels declined. Subsequent deeper pumping below fine-grained beds resulted in responses typical of confined aquifers. Larger hydraulic-head declines resulting from smaller storage coefficients caused the development of large vertical hydraulic gradients, aquifer-system compaction, and a greater significance of reduction in pore volume as a source of water.

A five-layer numerical model was constructed to represent the aquifer system using MODFLOW and a module for simulating aquifer-system compaction, IBS1 (Interbed Storage package #1), by Leake and Prudic (1991). The upper layer represents shallow interbedded alluvial deposits and was simulated as a water-table aquifer with instantaneously draining interbeds. The middle three layers represent the compressible part of the middle confining bed. Layer 2 is the upper 25 m of the confining bed, and layer 3

PWS-0196-0029

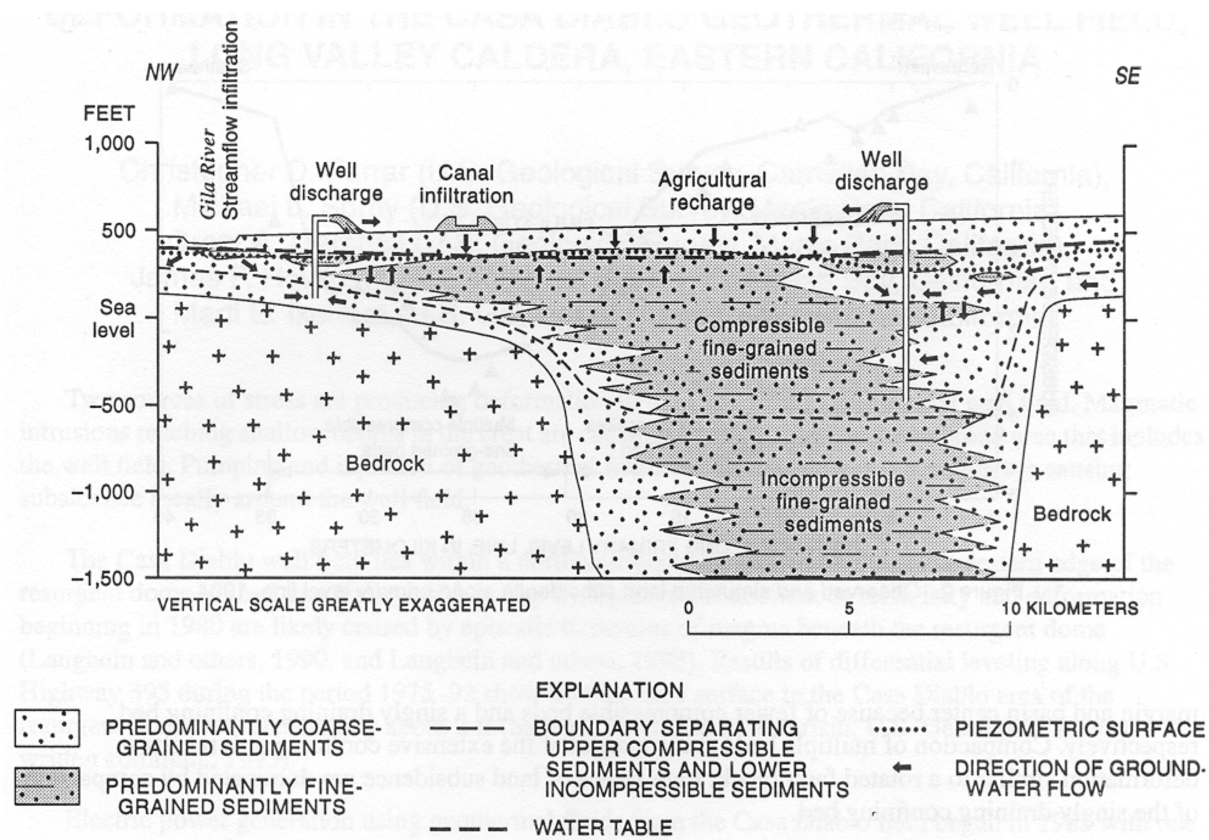


Figure 1. Generalized hydrogeologic section of Picacho Basin showing conceptual transient ground-water flow system.

is the next lower 50 m. Layer 4 is the rest of the compressible sediments in the confining bed. This vertical discretization of the upper part of the confining bed allows simulation of the delayed drainage from the bed. Also, the thickness of layers 1 and 2 represents the thickness of the aquifer system penetrated by a vertical extensometer. Layer 5 represents the lower incompressible confined aquifer.

Mean errors in the simulation of water levels in the upper aquifer system at 14 control points were 4 m throughout the 98 years of simulation, but average absolute errors increased from 5.1 to 19.1 m between simulations of 1950 and 1965 conditions. Most of this error probably is related to delayed drainage of confining beds and vertical hydraulic gradients in the upper layer, both of which were not simulated. The magnitude and sense of the water-level error in later years are similar to standard errors of estimated water levels derived from Kriging analysis and gridding of water-level data. Mean and average absolute land-subsidence errors for simulation of 1984 conditions were 0.17 and 0.30 m, respectively, at 23 bench marks along a primary level line across the main land-subsidence area. Observed land subsidence ranged from 0 to 3.8 m along the level line (fig. 2).

Definition of the thickness and distribution of compressible beds is one of the most important considerations in simulation of compaction in the Picacho Basin. The greatest amount of subsidence is coincident with the greatest number of compressible fine-grained beds that occur at the margin of the middle confining bed (fig. 2). Lesser amounts of compaction and land subsidence occur on the basin

PWS-0196-0030

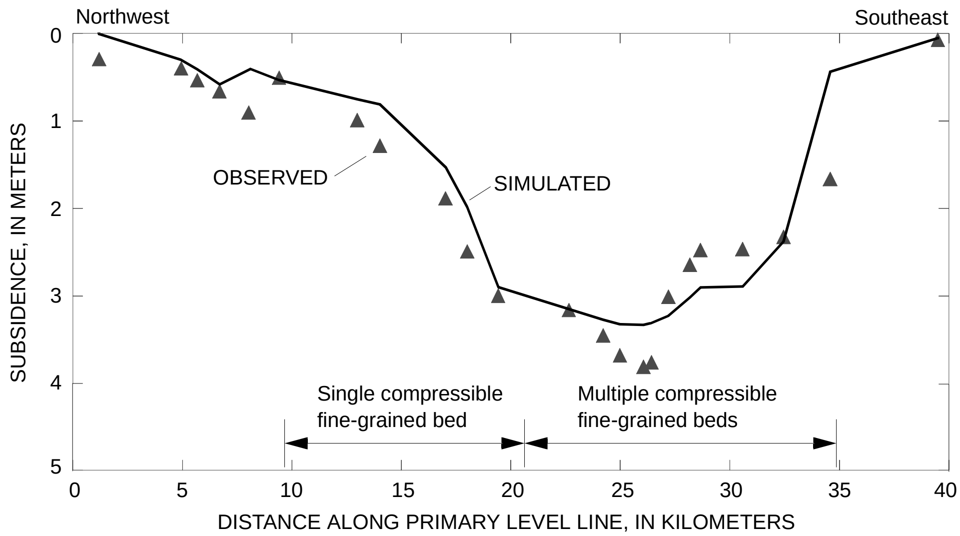


Figure 2. Observed and simulated land subsidence along primary level line, 1984.

margin and basin center because of fewer compressible beds and a singly draining confining bed, respectively. Compaction of multiple beds at the margin of the extensive confining unit results in deformation similar to a rotated fault block. Late stages of land subsidence are dominated by compaction of the singly draining confining bed.

Hydraulic information important to simulation of aquifer-system compaction in the Picacho Basin includes spatial distributions of stress and compaction, specific storage, and vertical hydraulic conductance. Knowledge of stress distributions is useful for model calibration but probably is rare in most basins as in the Picacho Basin. In aquifer systems that include slowly draining confining beds, spatial distributions of compaction are needed to calibrate storage properties and vertical hydraulic conductance. The vertical distribution of compaction can be monitored with partially penetrating vertical extensometers and Global Positioning System surveys of land subsidence. Vertical-extensometer data also are useful in establishing representative specific storage and vertical hydraulic-conductance values. A history of land-subsidence distributions alone is inadequate for calibration of storage properties and vertical hydraulic conductance in aquifer systems such as the Picacho Basin.

Results of model simulations indicate that release of water from storage in fine-grained beds became an increasingly significant source of water as development occurred. Most of the water budget for the transient-flow period is dominated by ground-water withdrawal for agriculture, storage depletion through pore drainage, and agricultural recharge. However, rates of water released through reduction in pore volume are similar in magnitude to flow rates at head-dependent boundaries and rates of natural recharge. Reduction in pore volume represents about 10 percent of storage depletion during mid-stages of development and as much as 25 percent during late stages of development.

PWS-0196-0031

DEFORMATION IN THE CASA DIABLO GEOTHERMAL WELL FIELD, LONG VALLEY CALDERA, EASTERN CALIFORNIA

Christopher D. Farrar (U.S. Geological Survey, Carnelian Bay, California),
Michael L. Sorey (U.S. Geological Survey, Menlo Park, California),
Grant A. Marshall (U.S. Geological Survey, Menlo Park, California),
James F. Howle, (U.S. Geological Survey, Carnelian Bay, California), and
Marti E. Ikehara (U.S. Geological Survey, Sacramento, California)

Two sources of stress are producing deformation in the Casa Diablo geothermal well field. Magmatic intrusions reaching shallow depths in the crust are causing regional inflation over a broad area that includes the well field. Pumping and injection of geothermal fluids for electric power generation are causing subsidence locally around the well field.

The Casa Diablo well field lies within a northwest-trending graben on the southwestern edge of the resurgent dome in the Long Valley caldera (fig. 1). Episodes of anomalous seismicity and deformation beginning in 1980 are likely caused by episodic intrusions of magma beneath the resurgent dome (Langbein and others, 1990, and Langbein and others, 1993). Results of differential leveling along U.S. Highway 395 during the period 1975–92 show that the land surface in the Casa Diablo area of the resurgent dome was elevated by about 2 ft (Savage, 1988, and D. Dzurisin, U.S. Geological Survey, written commun., 1993).

Electric power generation using geothermal fluids from the Casa Diablo field began in 1985 with one binary powerplant (MP I). Two additional powerplants (MP II and MP III) were put on line in December 1990. The power-generation process cools the geothermal fluid by about 60 ^{o}C in a closed-loop system. All the fluid that is pumped from wells on the western side of the well field from depths of about 500 ft is injected on the eastern side of the field at depths that have ranged from about 1,500 to 2,500 ft. In July 1991, shallow perforated sections in all injection wells were sealed, forcing injection of fluids to depths greater than 2,000 ft.

In 1985 localized subsidence around Casa Diablo began to counter the uplift of the well field area caused from magmatic intrusions under the resurgent dome. This local subsidence began within about 6 months of the start of geothermal fluid pumping at Casa Diablo. Results from leveling surveys show that Casa Diablo subsided about 0.38 ft between 1988 and 1992 relative to bench marks outside the area of subsidence, which had risen about 0.34 ft.

Each of the following processes may be occurring and causing deformation related to the geothermal operation: subsidence and inflation caused by changes in pore pressures in the production and injection reservoirs and adjacent formations, expansion and contraction of rocks caused by temperature changes in the reservoirs and overlying formations, and subsidence from loss of mass caused by escape of steam from boiling zones.

Data from the “L-shaped tilt array,” a network of closely spaced bench marks along two nearly perpendicular legs (see fig. 1) are shown in figure 2 as north and east components of tilt in microradians per year. The first significant tilt began in 1985 after the start-up of MP I. The downward tilt to the north increased by a factor of about three following a fourfold increase in pumping when power plants MP II and III were started in December 1990.

PWS-0196-0032

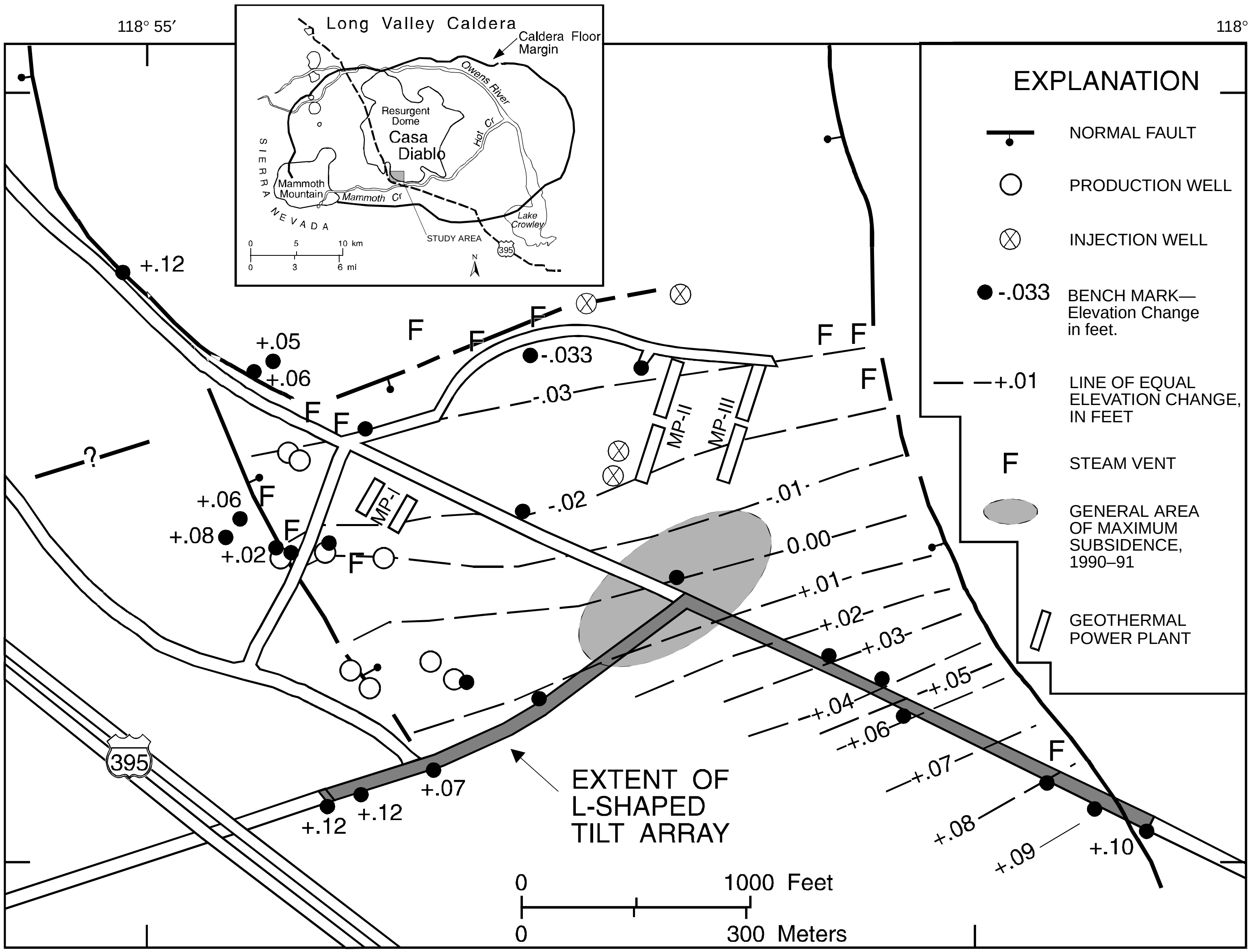


Figure 1. Elevation changes at Casa Diablo, 1991–92. Insert shows location of the Casa Diablo study area within the Long Valley caldera.

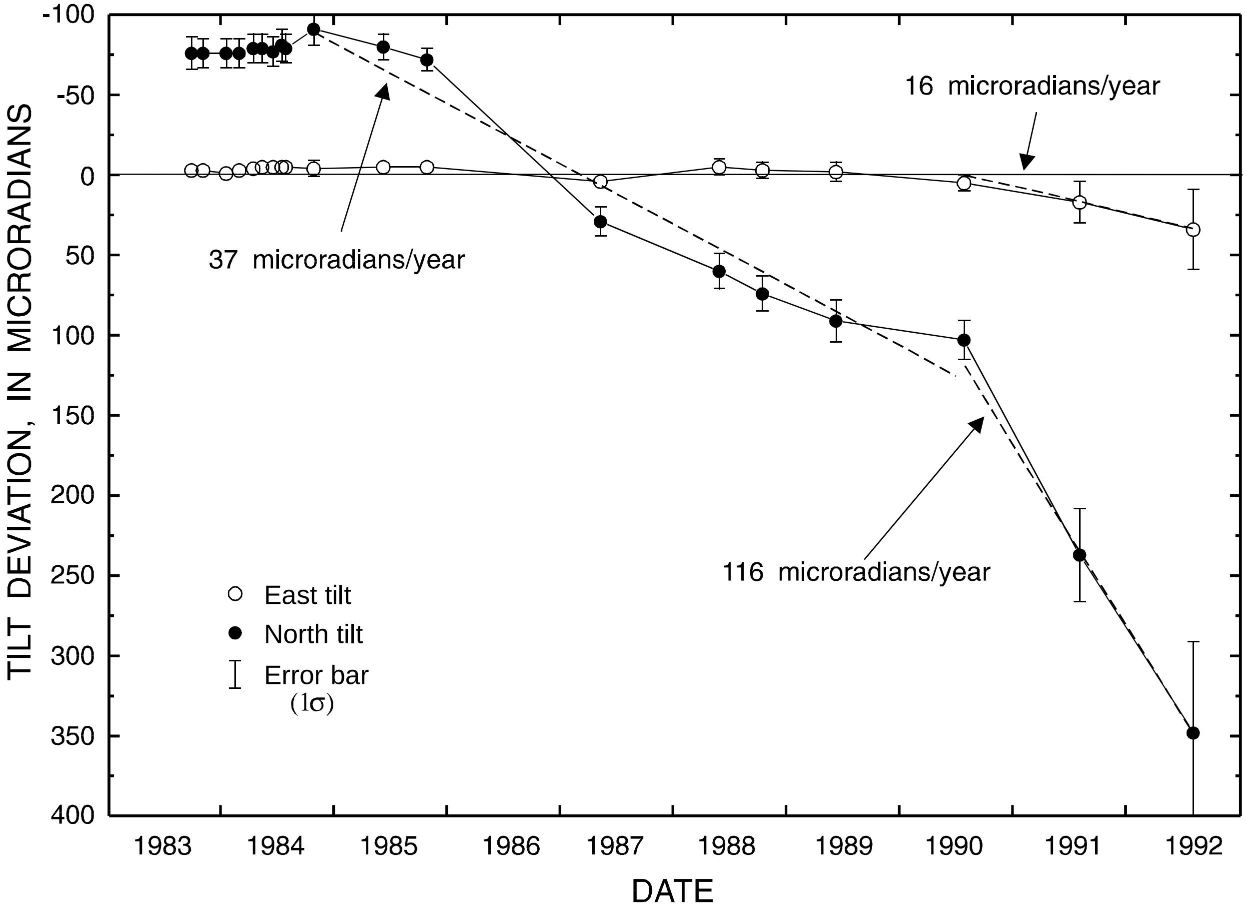


Figure 2. Calculated tilt from elevation changes along L-shaped bench-mark array at Casa Diablo. Dashed lines show average tilt per year for 1984–90 and 1990–92.

In June 1988 a network of bench marks was established in the well field to provide for more detailed measurement of deformation caused by pumping geothermal fluids (see Ikehara #1 abstract). Data from this network show that prior to 1992 the location of maximum subsidence around the well field was east of the production wells (fig. 1). This area is underlain by compressible unsilicified-rhyolite that occurs in the central part of the graben.

In 1992 the area of maximum subsidence shifted to the northwest and now includes both the production and injection sides of the well field. The change may have been brought about by the work done on the injection wells in July 1991, which sealed off shallow zones. The sealing of shallow zones caused the pore pressure in the production reservoir to fall sufficiently to allow boiling in the upper part of the production reservoir and overlying formations. Steam from the boiling process can escape to the atmosphere along faults and fracture zones. Steam discharge around the well field was noted to have increased significantly during 1991. Subsidence is uniform across the well field from injection to production sides, making it unlikely that thermal-elastic effects are responsible for the deformation observed between 1991 and 1992. It is probable that the greater degree of isolation of the injection and production reservoirs brought about by sealing off the shallow injection zones has allowed the pressure-drop in the production reservoir to spread across the well field to include the injection and production sides.

The two northwest-trending graben-bounding faults and the northeast-trending cross-fault (fig. 1) may exert some control over the spread of subsidence away from the well field. Changes in bench mark elevations between 1991 and 1992 suggest that the floor of the graben is pivoting downward to the northwest. Changes in pore pressure along the fault planes in response to fluid injection may be decreasing the coefficient of friction, thereby facilitating slippage along the faults.

PWS-0196-0035

SUBSIDENCE AND GROUND FISSURES IN THE SAN JACINTO BASIN AREA, SOUTHERN CALIFORNIA

Douglas M. Morton, (U.S. Geological Survey and Department of Earth Sciences, University of California, Riverside, California)

The San Jacinto basin is an extraordinarily deep and narrow pull-apart basin located at a right step in the San Jacinto fault zone, an important fault zone of the San Andreas fault system in southern California. The basin ranges in width from 3 to 4 km. The thickness of sedimentary fill within the basin is on the order of 3 km (Fett, 1968; Shawn Biehler, oral commun., 1988). The basin is bounded on the east by the Claremont fault and on the west by the Casa Loma fault (fig. 1). Both the Casa Loma and the Claremont faults are major strands of the San Jacinto fault zone. Within the area of the San Jacinto basin, the east-dipping Casa Loma fault has components of right-slip and normal-slip, and the similar dipping Claremont fault has components of right-slip and reverse-slip. The scarp of the Casa Loma fault is a relatively subtle and low scarp whereas the scarp of the Claremont fault is bold, rising to over 600 m above the basin floor (Morton and Sadler, 1989). The high Claremont scarp, due to the reverse-slip component, is produced by regional compression and uplift to the east and northeast of the San Jacinto basin. At the turn of the century most of the basin was an artesian basin (Waring, 1919).

Basin fill is supplied primarily by the San Jacinto River, which drains a large part of the San Jacinto Mountains area to the east of the San Jacinto basin. The San Jacinto River enters the east end of the basin and flows northwest along the length of most of the basin. At the north end of the basin additional fill is derived from a thick section of Pliocene continental sedimentary rocks on the east side of the Claremont fault. At the north end of the basin is a closed depression that contains ephemeral Mystic Lake. The closed depression at the north end of the basin is not the result of more rapid subsidence than elsewhere in the basin, but rather the lack of sufficient sedimentary material needed to balance subsidence. Tectonic subsidence and subsidence related to aquifer-system compaction has been well documented for the basin (Fett and others, 1967; Lofgren, 1976; Lofgren and Rubin, 1975; Morton, 1972; 1977). Tectonic subsidence for the past 40,000 years is in the range of 3 to over 5 mm/yr and has an average of about 4.5 mm/yr (fig. 2). The subsidence rates are based upon ^{14}C dates on wood samples collected from drill holes within the basin (see Hanson abstract for related discussions). The most visible expression of land-surface deformation is earth fissures, which are common in the northern part of the basin and several kilometers to the west.

Much of the aquifer system in the basin had a hydraulic head of about 3 m above land surface at the time of European settlement within the basin. By the end of the 1940’s very few flowing wells existed within the basin. In the early 1970’s ground-water withdrawal had lowered the hydraulic heads to about 24–30 m below land surface. Land subsidence has been attributed to aquifer-system compaction related to lowering of hydraulic heads (Lofgren, 1976). Releveling in the basin by the Metropolitan Water District between 1939 and 1959 indicates an average maximum annual rate of total land subsidence of about 3.5 cm (Proctor, 1962). An aqueduct pipe placed across the Casa Loma fault in 1958 was vertically deformed about 60 cm by 1973, for an annual rate of about 4 cm/yr (Morton, written commun., 1976). A highway resurvey in the early 1970's indicated a maximum rate of subsidence along the highway in the western part of the basin of about three cm/yr (Riverside County Road Department, oral commun., 1975). Considering the long-term tectonic rate of subsidence, land subsidence due to aquifer compaction caused by ground-water withdrawal is on the order to 2.5–3 cm/yr.

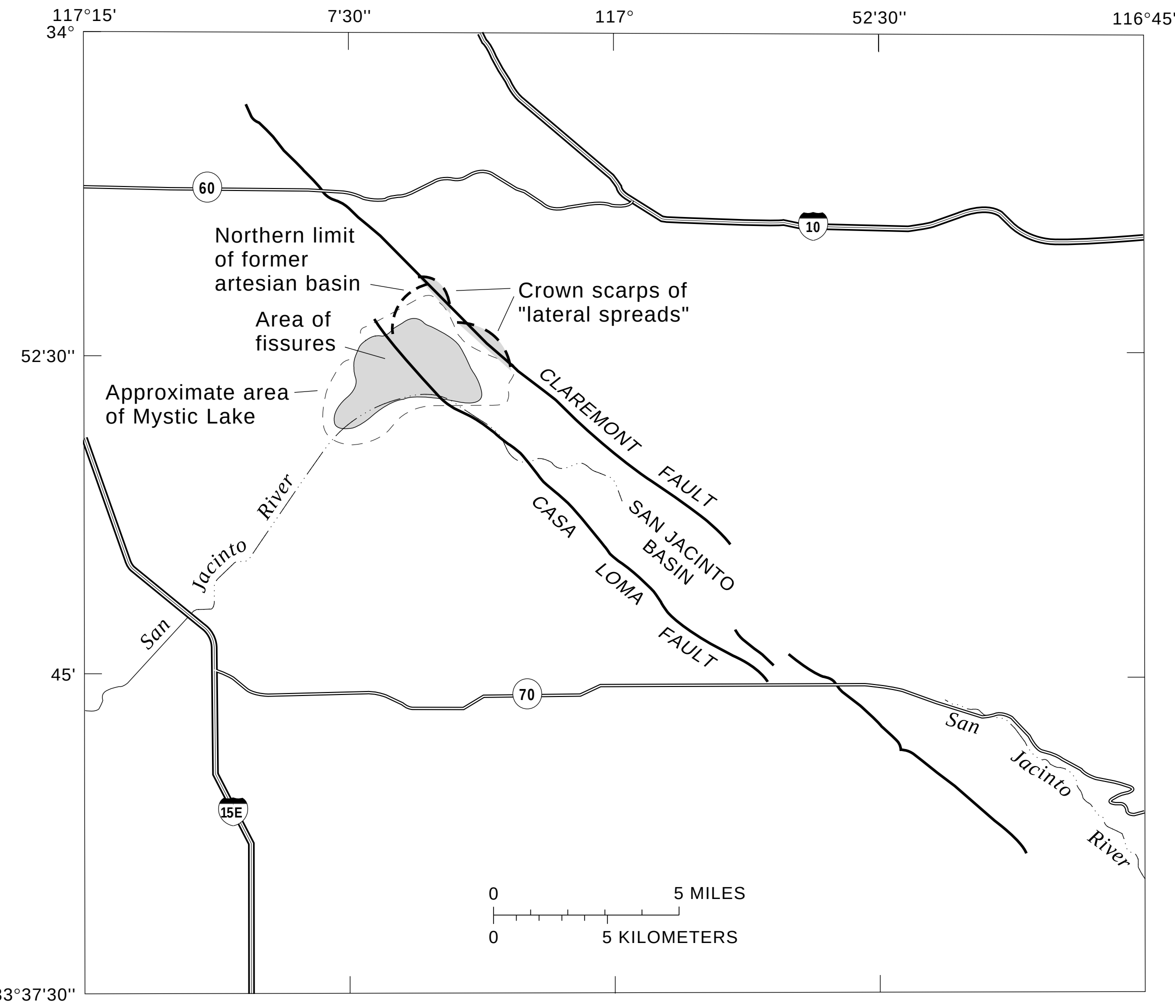


Figure 1. Generalized map of the San Jacinto basin area, California.

Earth fissuring, presumably consequent to the lowering of aquifer-system hydraulic heads, apparently first became evident in the early 1950's. (See Schumann, Ward and others, and Haneberg and Friesen abstracts for discussions of other earth fissures; also see Haneberg and Helm abstracts for possible mechanisms of earth fissure formation.) Most of the fissures occur on nearly horizontal ground. In the early 1950's most of the fissuring was limited to a relatively small area about 1 km long in the basin and another small area, 1.5 km long west of the basin (Morton, 1977). A few scattered fissures were reported from near the Claremont fault in the southeastern part of the basin (Fett and others, 1967). These early fissures were relatively short, most being 100–200 m long. By 1973 fissuring had greatly expanded both within the basin and to the west over an area of about 18 km^2. In addition, a few isolated fissures were located as far as 4 km west of the main area of fissures. The fissuring to the west of the basin occurred over the northern part of a several hundred-meter-deep, west-oriented, sediment-filled canyon. As the fissures grew in number they also grew in length. A number of fissures had a length over 1 km by 1973 (Morton, 1977). Some of the older fissures have been filled with sediment so little if any surface expression remains, while others have been periodically reactivated and lengthened with reactivation. By the late 1970's a few long fissures, about 1 km in length, developed west of the basin at a distance of about 10–12 km south of the main area of fissures. Some of these isolated fissures were reactivated in 1992.

PWS-0196-0037

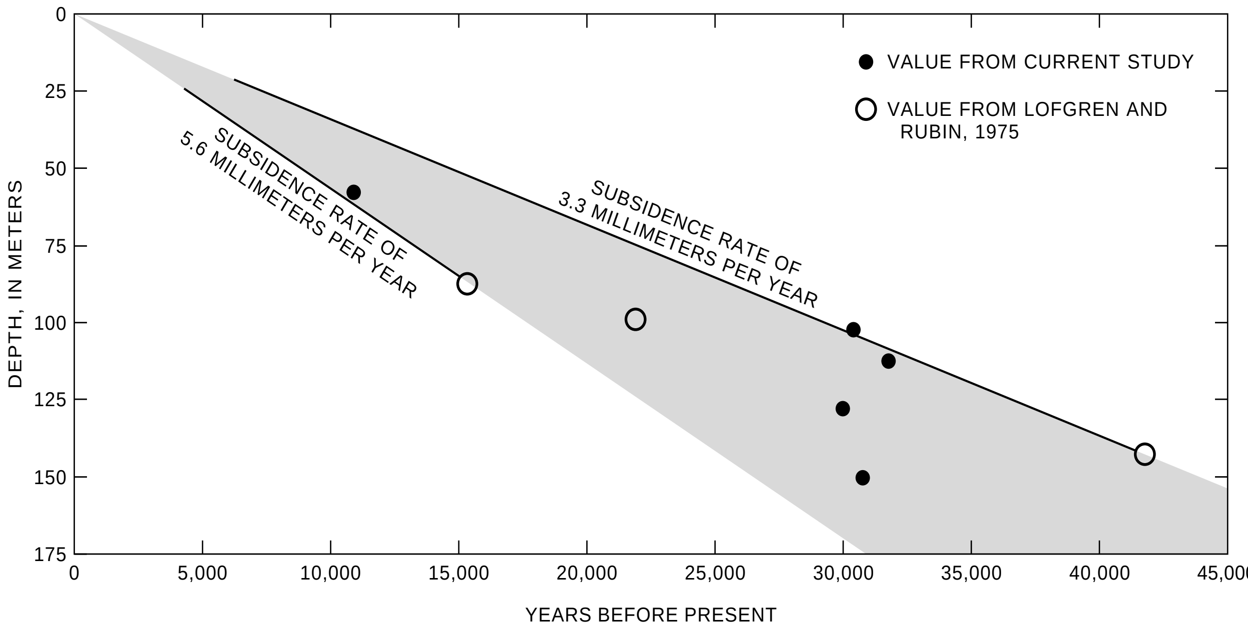


Figure 2. Depth and ages of C14 dated material from the San Jacinto basin, California, and inferred rates of subsidence.

In the late 1980's a different form of fissuring started along the east side of the northern part of the basin. Here on gentle slopes extending east from the Claremont fault are large areas that are underlain by material slowly moving downslope into the basin (Morton and Sadler, 1989). These features are somewhat like slow-moving "lateral-spread" landslides. The width of the larger features is more than 1 km. A discontinuous scarp is produced at the head of the moving mass, and some lateral zones of deformation form in the upper lateral part of the moving mass. Vertical displacement of the scarp area of one of these masses was as much as 1 m over a 2-year period in the late 1980's. Extensional fissures developed in the headward parts of the mass moving away from the scarp area. The morphology of these fissures resemble those fissures within the basin.

LAND SUBSIDENCE IN THE OXNARD PLAIN OF THE SANTA CLARA–CALLEGUAS BASIN, VENTURA COUNTY, CALIFORNIA

Randall T. Hanson (U.S. Geological Survey, San Diego, California)

The Oxnard Plain is one of 10 ground-water subbasins within the coastal valleys and plains of the Santa Clara–Calleguas Basin in Ventura County, California (fig. 1). The plain is underlain by a complex aquifer system that has been the primary source for water supplies since the early 1900's. Oil and gas has been produced in the Santa Clara–Calleguas Basin since the 1920's and in the Oxnard Plain since the 1940's. The basin is a part of the tectonically active Transverse Range physiographic province. Ventura County has delineated a probable-subsidence-hazard zone that includes parts of the Piru, Fillmore, Santa Paula, Mound, Montalvo, Oxnard Plain, and Pleasant Valley subbasins (Ventura County Board of Supervisors, 1988). Ground-water withdrawal, oil and gas production, and tectonic movement are three potential causes of subsidence in the Oxnard Plain and adjacent subbasins.

Water-level declines in the upper- and lower-aquifer systems have ranged from about 50 to 100 ft in the Oxnard Plain since the beginning of ground-water development in the early 1900's. Water-levels in the lower-aquifer system at multiple-level observation wells range from 20 ft lower than the upper aquifer system near Port Hueneme along the central coast to about 80 ft lower than the upper aquifer system near the Naval Air Station, Point Mugu, along the southern coast of the Oxnard Plain. Early pumpage data is unavailable for the Oxnard Plain, so the total amount of water withdrawn remains unknown. However, recent pumpage data indicate that during 1979–91 about 822,000 acre-ft of ground water was withdrawn at a relatively constant annual rate, in the Oxnard Plain.

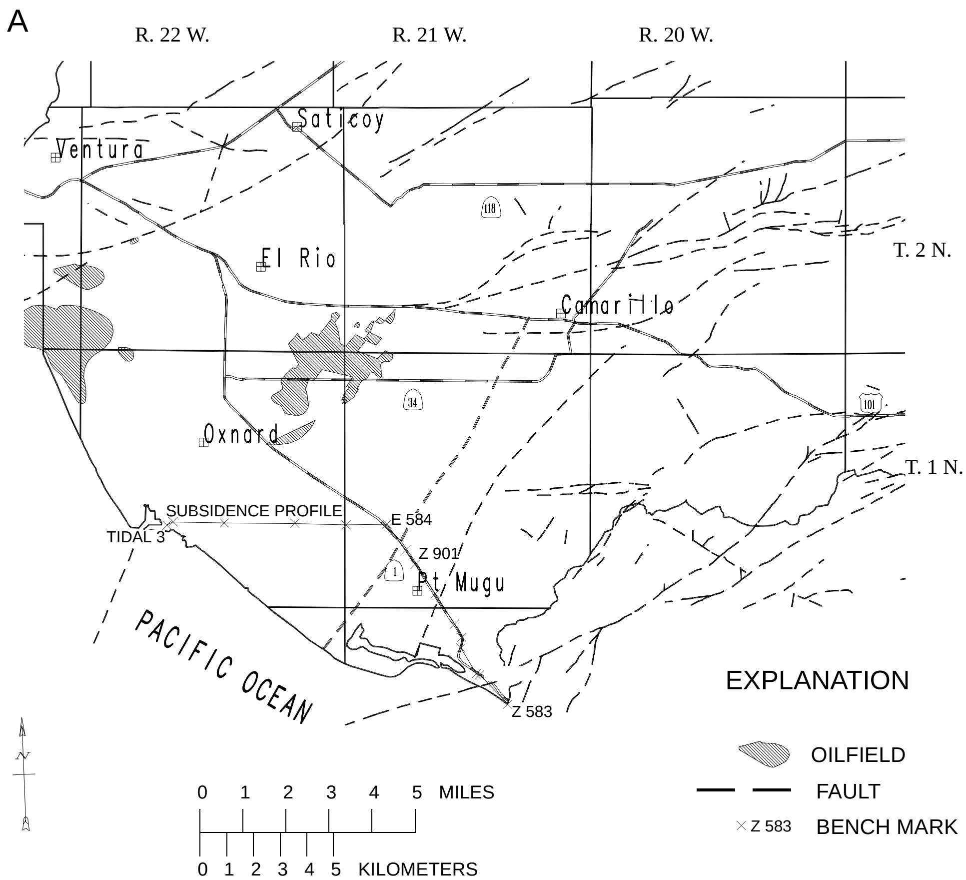
More than 7,900 acre-ft of brines, 8,000 acre-ft of oil, and 72 million ft^3 of natural gas were withdrawn between 1943 and 1991 from oil fields in the Oxnard Plain subbasin (Steven Fields, Operations Engineer, California Department of Conservation, Division of Oil and Gas, written commun., 1992). Pressure declines in the Oxnard oil fields equivalent to more than 1,100 ft of water-level decline have occurred since the onset of oil and gas production. These declines alone could account for potential local subsidence on the order of 1.5 to 2.0 ft.

Tectonic activity in the form of plate convergence and north-south crustal shortening has resulted in an average regional horizontal movement of about 0.007 ft/yr over the past 200,000 years (Yeats, 1983) in the subbasins north of the Oxnard Plain. The vertical movement in the form of uplift north of the Oxnard Plain and as subsidence in the Oxnard Plain is caused by plate convergence and related earthquakes throughout the basin. At the southern edge of the Oxnard Plain (fig. 1A), bench-mark data on bedrock (at BM Z 583) indicate that 0.17 ft of subsidence occurred during 1939–78, at a rate of about 0.004 ft/yr, that could be related to tectonic activity (see Morton abstract for related discussions).

Bench-mark data along a coastal leveling traverse near the southeastern edge of the Oxnard Plain (fig. 1A, B) indicate that as much as 1.6 ft of subsidence occurred during 1939–60 at bench-mark E 584 (0.07 ft/yr) and an additional 1 ft occurred during 1960–78 (0.06 ft/yr). An additional 0.5 ft of subsidence during 1960–92 was measured at bench-mark Z 901 southwest of BM E 584 along the coastal edge of the Oxnard Plain. Farther inland, where water-level and oilfield pressure declines are largest, greater subsidence might be expected.

Indirect evidence for subsidence that is potentially related to ground-water withdrawals includes water-level declines in excess of 100 ft, subsurface collapse of well casings, repeated regrading of irrigated fields for proper drainage, and degraded operation of drainage ditches in agricultural areas. In the Las

PWS-0196-0039



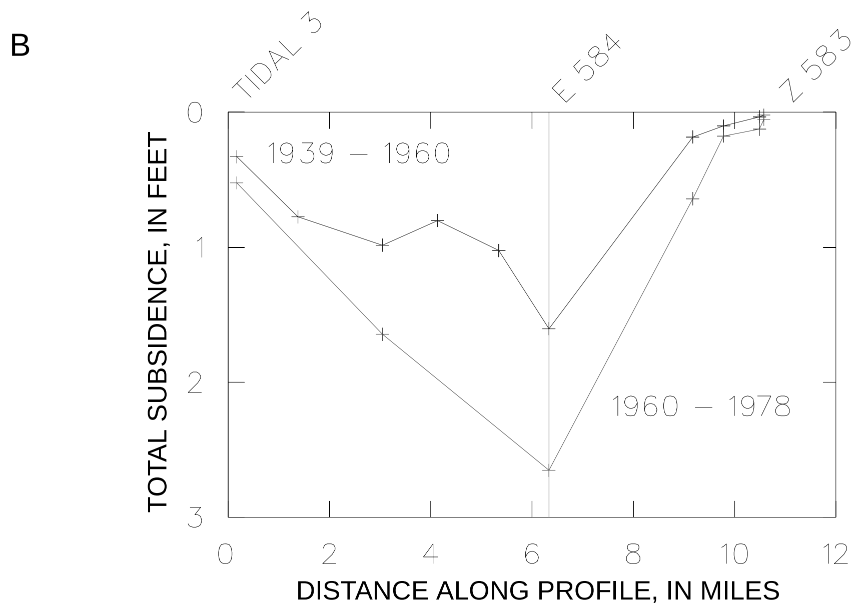


Figure 1. Subsidence in Oxnard Plain and Pleasant Valley, Santa Clara–Calleguas Basin, Ventura County, California. *A*, Geographic features. *B*, Subsidence profile.

PWS-0196-0040

Posas and Pleasant Valley subbasins, water-level declines of 50 to 100 ft have occurred in the upper aquifer system and declines of 25 to 300 ft or more have occurred in the lower aquifer system since the early 1900's. On the basis of large water-level declines, the area of probable subsidence may be larger than that previously delineated by Ventura County and may include Las Posas Valley and the remainder of Pleasant Valley. By 1992, total subsidence in the Oxnard Plain could exceed the 2.6 ft measured during 1939–78 along the coastal traverse. Ground-water withdrawal and oil and gas production may be major sources of subsidence in the Oxnard Plain, and tectonic activity probably is a minor source. Delineation of the relative contributions from the three sources and the spatial and temporal distribution of subsidence, would require the installation of extensometers, in combination with accurate bench mark and microgravity monitoring networks.

GEOLOGIC SETTING OF EAST ANTELOPE BASIN, WITH EMPHASIS ON FISSURING ON ROGERS LAKE, EDWARDS AIR FORCE BASE, MOJAVE DESERT, CALIFORNIA

A.Wesley Ward (U.S. Geological Survey, Flagstaff, Arizona),
Gary L. Dixon (U.S. Geological Survey, Las Vegas, Nevada), and
Robert C. Jachens (U.S. Geological Survey, Menlo Park, California)

In late January of 1991, a large earth fissure formed on the playa surface at the southeast end of Rogers Lake at Edwards Air Force Base (see Blodgett abstract for additional discussion of land-surface deformation of Rogers Lake). Much insight was gained regarding the origin of the fissure through the integration of information obtained from recent regional geologic, geophysical, and hydrologic studies. Pertinent questions are whether the fissure is tectonic or hydrologic in origin and whether future occurrences are likely or predictable. In addition to addressing these questions, recent studies (Dixon and Ward, 1994a, b; Ward and Dixon, 1994a, b) have refined the regional late Tertiary and Quaternary geologic history of the East Antelope Basin, a depocenter for upper Tertiary, lower Quaternary sediments.

Local rock units in the area include tuffs, lava flows, and sediments of the Tropico Group of Tertiary age, Tertiary fanglomerates, Tertiary intrusive rhyolites and dacites, and deeply weathered Mesozoic granitic rocks. Exposed Quaternary geologic units include sandy alluvium, playa clays, and beach deposits; these are of late Quaternary age and related to pluvial Lake Thompson, the remnants of which form the playas (Rosamond, Buckhorn, and Rogers Lakes).

Mabey (1960) first recognized the East Antelope Basin from a 40-mGal gravity low and suggested that the steep gravity gradients may be fault controlled. The gravity signature suggests that this northeast-trending basin (fig. 1) is deepest just southwest of Rosamond Lake and becomes shallow to the northeast. We confirm this as a structural basin not only from gravity data (fig. 2 (Morin and others, 1990), but also from a series of resistivity anomalies (Zohdy and Bisdorf, 1990; 1991), subtle surface escarpments, alignment of historical springs, now dry, which trend N30–45° E, and steep aquifer hydraulic-head gradients. The southeast boundary of the basin is much less apparent, but is definable from field observations and geophysics.

During mid-Quaternary time, a drainage reversal occurred in the region as a result of uplift of the San Gabriel Mountains, and activity along northwest-trending faults blocked the southwest flow of water out of the basin, thus creating Lake Thompson. As the climate became more arid, water sources were depleted; today remnants of Lake Thompson remain in the form of Rosamond, Buckhorn, and Rogers Lakes.

Hydrologically the basin is part of the Lancaster ground-water subbasin and is a source for agricultural, municipal, and industrial ground-water supply in the Antelope Valley area, as well as the primary source of water for Edwards Air Force Base (see Londquist abstract for additional information on the hydrogeology of the Antelope Valley; Londquist and others, 1993).

The fissure on Rogers Lake (fig. 1) is approximately 1–2 m wide, 1.16 km long, and extends to an unknown depth. Although somewhat sinuous, its average trend is within a few degrees of north. Known and inferred faults in the immediate area trend northwest; the extent of the El Mirage Fault mapped by Dibblee (1967) has been reinterpreted to extend beneath south Rogers Lake near the fissure and continue to the northwest, connecting with the Bissell Hills Fault. The fissure occurs near a local gravity low (fig. 2) that defines the northeastern subbasin of the East Antelope Basin, a subbasin we infer to be more than

PWS-0196-0042

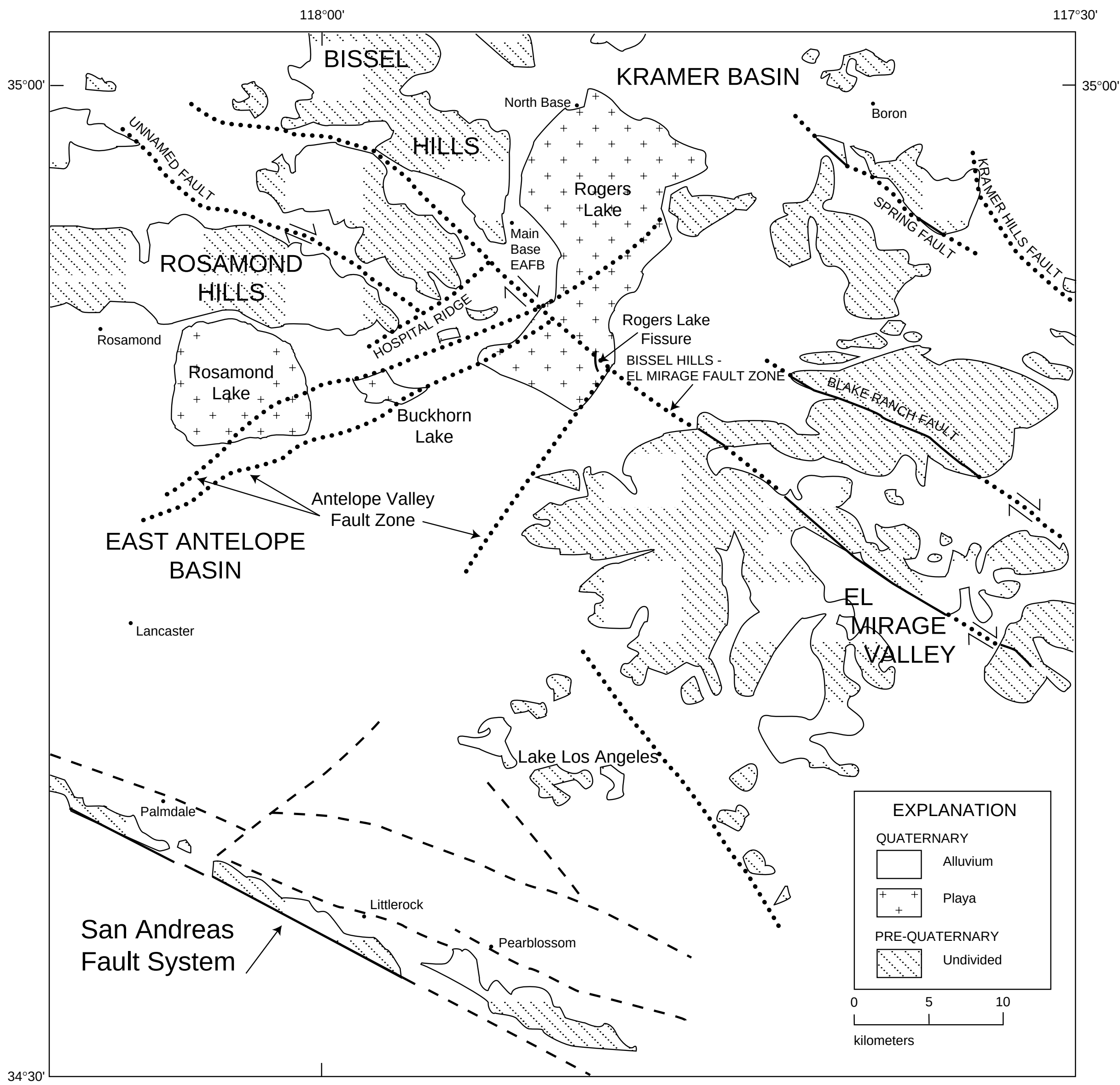


Figure 1. Generalized geologic map of the East Antelope Basin area (modified from Mabey, 1960).

600 m deep. The shape of the basement beneath this sediment-filled subbasin is reflected in the gravity contours that bound the gravity low, which trend at angles of 45° or more from the trend of the fissure. Based on the trends of the major faults in the area, the trends of the gravity contours that define the local subbasin beneath the fissure, and the gravity interpretation that the fissure occurs over a deep part of the basin, argue against a fault-controlled origin of the fissure. More likely, the fissure may have been caused by differential compaction over some nontectonic structure within the sedimentary section, rather than by extensional strain on sediments on a convex-upward basement surface (see Haneberg and Helm abstracts for possible mechanisms of earth-fissure formation).)

PWS-0196-0043

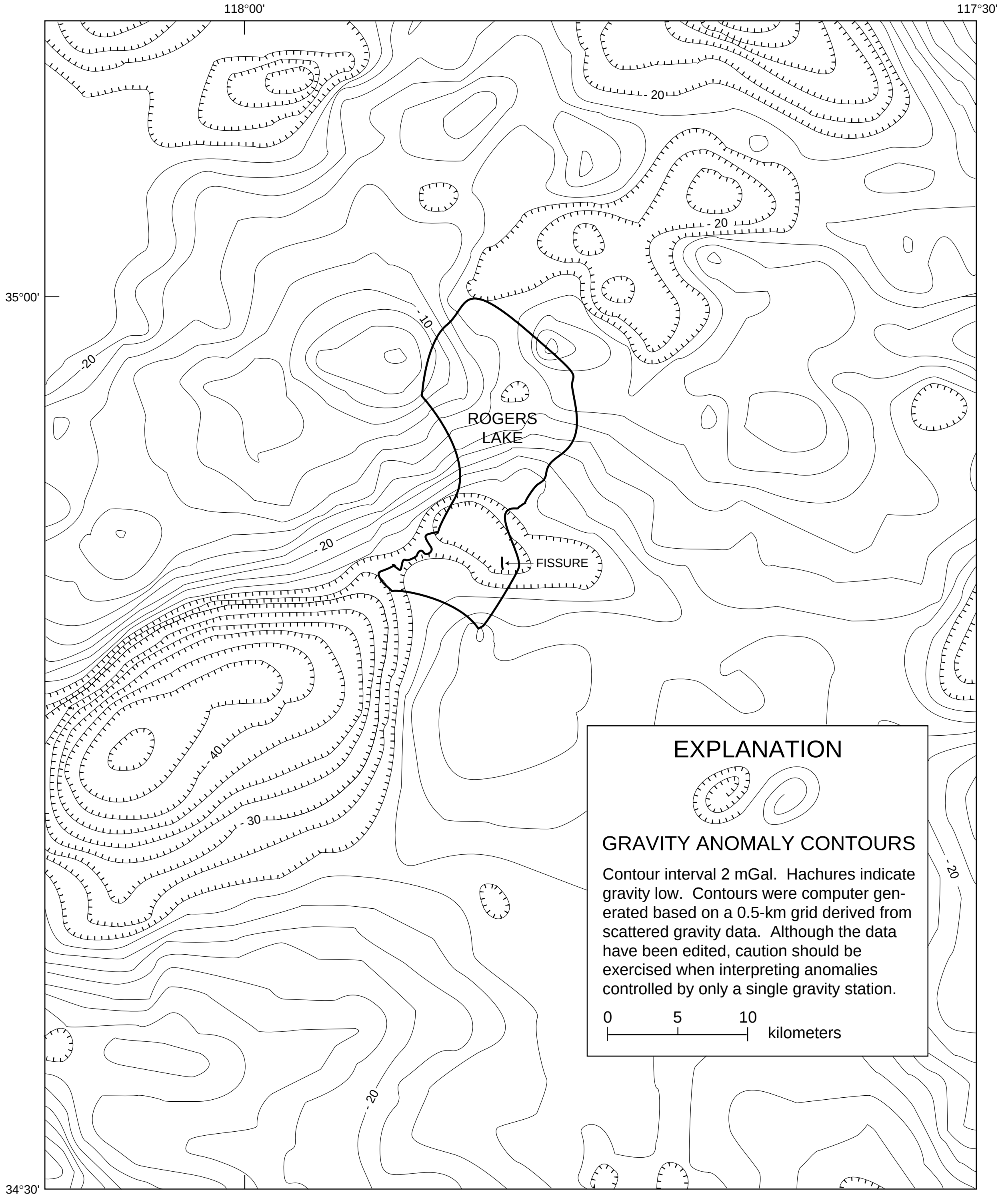


Figure 2. Isostatic residual gravity map of the East Antelope Basin area (Morin and others, 1992).

PWS-0196-0044

HYDROGEOLOGY AND LAND SUBSIDENCE, ANTELOPE VALLEY, CALIFORNIA

Clark J. Londquist (U.S. Geological Survey, Sacramento, California)

The Antelope Valley lies in the western Mojave Desert of southern California, about 60 mi north of Los Angeles (fig. 1) The Antelope Valley is a closed topographic basin that covers about 2,200 mi^2, and has its lowest point in the Rogers and Rosamond Dry Lakes area. The valley is bounded on the southwest by the San Gabriel Mountains and the San Andreas Fault zone and on the northwest by the Tehachapi Mountains and Garlock Fault zone. The valley overlies three structural basins; the West Antelope, the East Antelope, and Kramer, which have been filled with as much as 10,000 ft of Tertiary and Quaternary sediments (Mabey, 1960). These sediments consist of a series of unconsolidated alluvial deposits interbedded with a thick layer of lacustrine deposits. Near the southern limit of the valley these lacustrine deposits are buried beneath as much as 800 ft of alluvium, but, to the north, near the southern end of Rogers Lake the lacustrine deposits are exposed at land surface. Borehole geophysical logs indicate that the alluvial deposits contain a high percentage of thin bedded, fine-grained silt and clay material (see Ward and others abstract for additional information on the geology of the Antelope Valley).

The aquifer system in the Antelope Valley consists of two alluvial aquifers known as the principal aquifer and the deep aquifer. The principal aquifer occurs in the Lancaster ground-water subbasin and overlies the lacustrine deposits extending over most of the valley south and west of Rogers Lake. The principal aquifer is the major source of ground water pumped in Antelope Valley. The deep alluvial aquifer underlies the lacustrine beds and extends to the north beneath Rogers Dry Lake and beyond. The deep aquifer is the major source of ground water pumped at Edwards Air Force Base (Londquist and others, 1993).

Ground water in the Antelope Valley area originates primarily from the infiltration of surface-water runoff from the San Gabriel and Tehachapi Mountains. Estimates of the average annual recharge to the aquifer system range from about 40,000 to 81,000 acre-ft (Durbin, 1978, and Wright, 1924). Ground-water use for irrigation in the valley began in the early 1900's and peaked in the 1950's. Estimates of the peak annual pumpage range from about 280,000 to 480,000 acre-ft (Snyder, 1955; California State Water Resources Control Board, 1974). After this peak period, ground-water use in the valley began to decline because of declining water levels, increasing energy costs, and the availability of imported water. The estimated annual ground-water pumpage in 1988 was about 62,000 acre-ft (Zettlemoyer, 1990).

The estimated ground-water pumpage from the Antelope Valley has exceeded the estimated annual recharge almost every year since the early 1920's. This imbalance is reflected in the declining aquifer hydraulic heads over most of the valley. In some areas there have been declines of more than 100 ft since the early 1950's, and indications are that declines before this period may have been as great or greater.

Both of the major elements necessary for land subsidence exist in the Antelope Valley: thick unconsolidated sections of sedimentary material that contain high percentages of fine-grained material and large hydraulic-head declines. Land subsidence was first reported in the Antelope Valley in the 1950's (Lewis and Miller, 1968) and by 1967 there had been as much as 2 ft of subsidence over an area of about 200 mi^2. Between 1961 and 1991 there was as much as 4 ft of subsidence in the City of Lancaster and more than 3 ft near the southern end of Rogers Lake (Blodgett and Williams, 1992; see Blodgett abstract for additional information on land-surface deformation near Rogers Lake).

PWS-0196-0045