U.S. Department of the Interior
U.S. Geological Survey

Detection and Measurement of Land Subsidence Using Interferometric Synthetic Aperture Radar and Global Positioning System, San Bernardino County, Mojave Desert, California

U.S. Geological Survey
Water-Resources Investigations
Report 03-4015

Prepared in cooperation with the **Mojave Water Agency**

science for a changing world

Detection and Measurement of Land Subsidence Using Interferometric Synthetic Aperture Radar and Global Positioning System, San Bernardino County, Mojave Desert, California

By Michelle Sneed[1], Marti E. Ikehara[2], Sylvia V. Stork[1], Falk Amelung[3], *and* Devin L. Galloway[4]

U.S. GEOLOGICAL SURVEY

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7002-04

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CONVERSION FACTORS

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
kilometer (km)	0.6214	mile (mi)
millimeter (mm)	0.03937	inch
millimeter (mm)	0.003281	foot (ft)
meter (m)	3.281	foot (ft)
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

VERTICAL DATUM

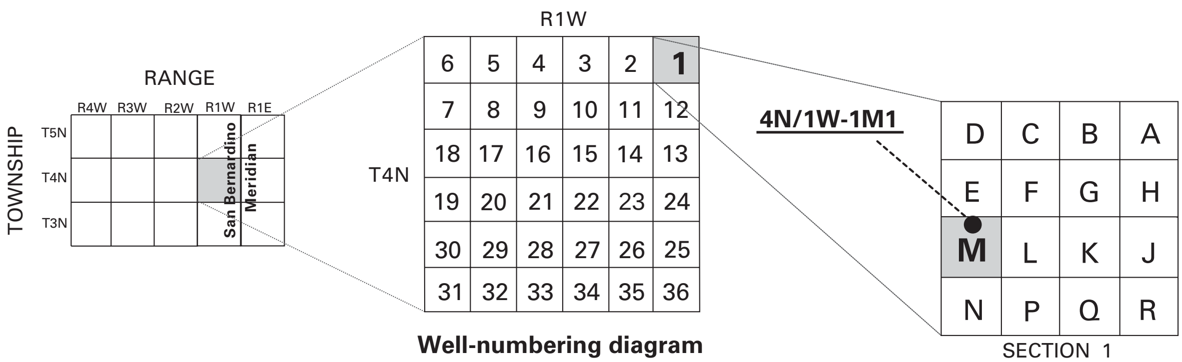
Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS

ERS	European Earth Remote Sensing satellites
GPS	Global Positioning System
HPGN	High Precision Geodetic Network
InSAR	interferometric synthetic aperture radar
MWA	Mojave Water Agency
NAD83	North American Datum of 1983
NGS	National Geodetic Survey
NGVD29	National Geodetic Vertical Datum of 1929
SAR	Synthetic aperture radar
USGS	U.S. Geological Survey

Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with “A” in the northeast corner of the section and progressing in a sinusoidal manner to “R” in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humbolt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referred to the San Bernardino base line and meridian (S). Well numbers consist of 15 characters and follow the format 004N001W01M001S. In this report, well numbers are abbreviated and written 4N/1W-1M1. The following diagram shows how the number for well 4N/1W-1M1 is derived.



Well-numbering diagram

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ABSTRACT

Land subsidence associated with ground-water-level declines has been recognized as a potential problem in parts of the Mojave Desert, California. Ground water has been the primary source of domestic, agricultural, and municipal water supplies in the desert since the early 1900s. Pumping of ground water from the Mojave River and Morongo ground-water basins in the southwestern Mojave Desert resulted in water-level declines of more than 30 meters (100 feet) between the 1950s and the 1990s.

A Global Positioning System (GPS) survey of a geodetic network was used to determine the location, extent, and magnitude of vertical land-surface changes in Lucerne Valley in the Morongo ground-water basin. The GPS survey was conducted in 1998 to estimate historical elevation changes by comparing GPS-derived elevations with historical elevations (which were available for some of the monuments in the network as early as 1944) and to establish baseline values that can be used for comparisons with future GPS surveys. The GPS measurements indicated that about 600 millimeters (2 feet) [plus or minus 1,500 millimeters (5 feet)] of subsidence occurred at three of the monuments between 1969 and 1998 but that very little to no vertical change in position occurred at seven other monuments in the network. Water levels in the area of subsidence in Lucerne Valley declined about 15 meters (50 feet) during 1970–98.

Interferometric synthetic aperture radar (InSAR) methods were used to characterize vertical land-surface changes in the Mojave River and Morongo ground-water basins during various intervals of time between 1992 and 1999. Interferograms, InSAR-generated displacement maps, show that subsidence ranging from 45 to 90 mm (0.15 to 0.3 ft) occurred in four areas of these two ground-water basins—the El Mirage, Lockhart–Harper Lake (dry), Newberry Springs, and Lucerne Valley areas. Some of the InSAR measurements were affected by the earthquakes at Landers and Hector Mine, California, and by atmospheric artifacts.

Water-level data were examined for areas undergoing vertical land-surface changes to determine whether the vertical land-surface changes may be related to aquifer-system compaction caused by ground-water-level changes. Temporally relevant water-level data were sparse for some areas, particularly the El Mirage and Lockhart–Harper Lake (dry) areas. Water levels in wells proximate to the subsiding areas generally declined between 1992 and 1999; water levels in some wells proximate to the subsiding areas experienced seasonal periods of declines and recoveries.

INTRODUCTION

The Mojave River and Morongo ground-water basins are in the southwestern part of the Mojave Desert in southern California, approximately 130 and 200 km (80 and 120 mi) northeast of Los Angeles (fig. 1), respectively. Surface water in these basins is minimal and normally is limited to ephemeral flow during winter and spring storms and to continuous flow from springs. Because of the lack of significant surface-water resources in these basins, ground water has been the primary source of water supply for domestic, agricultural, and municipal water consumption since the early 1900s. Increased demand on local water supplies owing to increasing urbanization has resulted in overdraft conditions in some areas of the Mojave River and Morongo ground-water basins and caused water levels in some wells to decline more than 30 m (100 ft) between the 1950s and the 1990s. Ground-water levels in some areas were lower in the 1990s than were the previously recorded low levels (Trayler and Koczot, 1995; Smith and Pimentel, 2000). These low water levels have the potential to induce or renew land subsidence (the lowering of land-surface elevations) in the Mojave River and Morongo ground-water basins. Land subsidence can result in disruption of surface drainage, reduction of aquifer-system storage capacity, formation of earth fissures, and damage to wells, buildings, roads, and utility infrastructure.

Because of concerns related to the potential for new or renewed land subsidence in the Mojave River and Morongo ground-water basins, the Mojave Water Agency (MWA) entered into a cooperative agreement with the U.S. Geological Survey (USGS) to assess land subsidence. The agreement included establishing a geodetic network of monuments to monitor land subsidence in the Lucerne Valley using GPS. In addition, spatially detailed maps were developed using interferometric synthetic aperture radar (InSAR) to determine changes in vertical land-surface elevation for the parts of the Mojave River and Morongo ground-water basin that are managed by the MWA.

This report presents the results of a comparison between elevation data for the monuments in the GPS network, determined from the GPS survey made in 1998, and historical elevation data for these monuments to determine whether land subsidence has occurred. Historical ground-water-level data were compiled and reviewed and then compared with the GPS measurements of the monuments for which elevation changes were significant. This report also presents spatially detailed maps developed using InSAR; the maps show vertical land-surface changes, or displacements, between 1992 and 1999 for intervals ranging from about 3 to 41 months. For areas where InSAR showed vertical land-surface displacements, ground-water-level data were examined to determine whether land-surface displacements were related to water-level changes.

The geodetic network used for the 1998 GPS survey is located only in the Lucerne Valley part of the study area. The InSAR-generated spatially detailed maps cover much of the southwestern Mojave Desert, but only the areas that showed land-surface displacements are discussed in this report. These areas are El Mirage, Lockhart–Harper Lake (dry), Newberry Springs, and Lucerne Valley (fig. 1).

DESCRIPTION OF STUDY AREA

The climate of the Mojave Desert region of southern California is characterized by low precipitation and humidity, and temperatures that range from above 38°C (100°F) in the summer to below 0°C (32°F) in the winter. Average annual precipitation ranges from 100 to 150 mm (4 to 6 in.) in the study area to more than 1,000 mm (40 in.) in the San Bernardino and the San Gabriel Mountain Ranges to the south of the study area (Lines, 1996). Recharge to the ground-water system from direct infiltration is minimal (Smith and Pimentel, 2000).

The Mojave River and Morongo ground-water basins have a combined area of about 6,200 km^2 (2,400 mi^2) (fig. 1). Although these basins are largely undeveloped, many of the desert communities in these basins are expanding. Agriculture is concentrated in and near the El Mirage, Lockhart–Harper Lake (dry), and Newberry Springs areas; along the Mojave River in the Mojave River ground-water basin; and in the Lucerne Valley area in the Morongo ground-water basin (Smith and Pimentel, 2000).

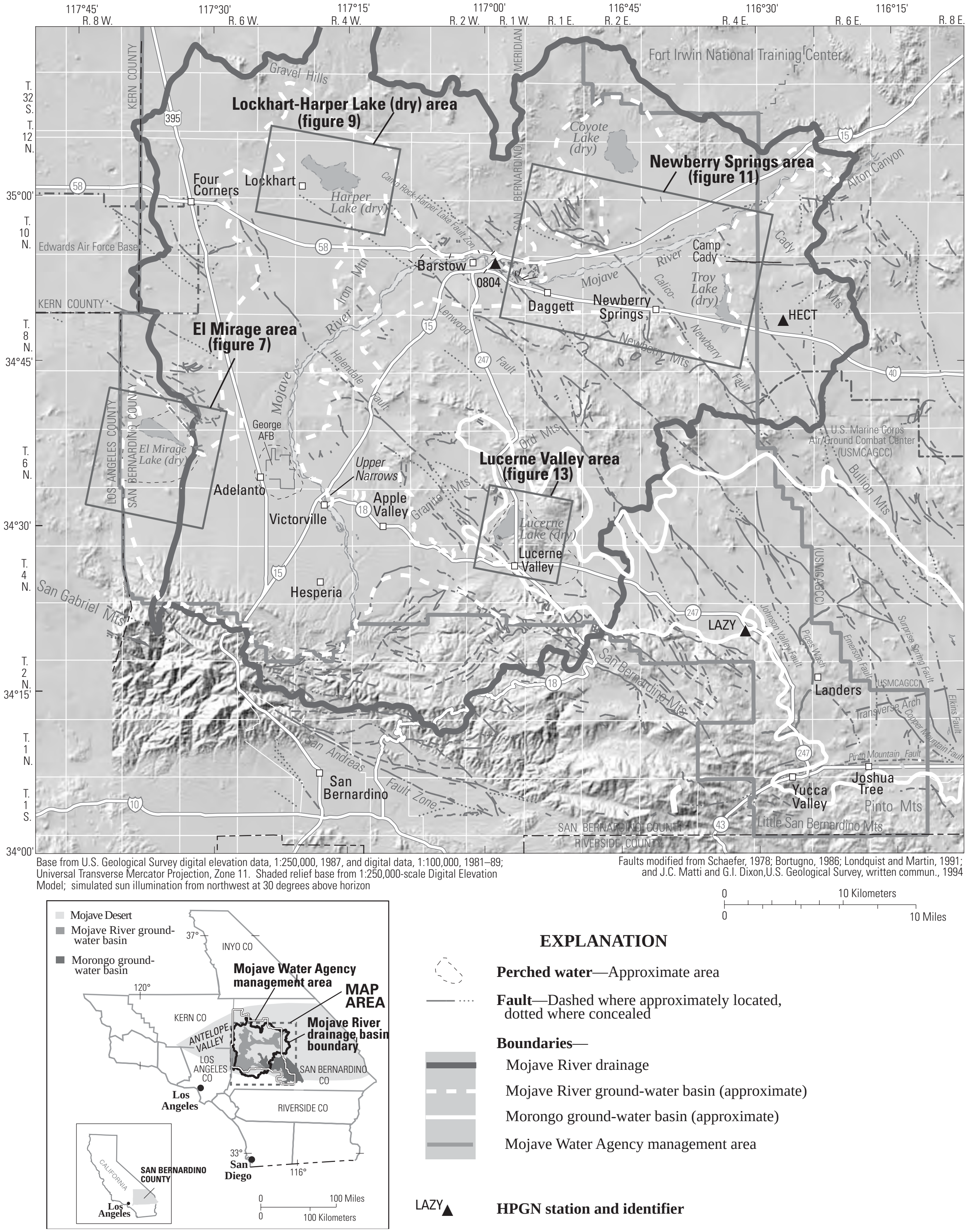


Figure 1. Locations of the Mojave River and Morongo ground-water basins, San Bernardino County, California, and of three High Precision Geodetic Network (HPGN) stations. Figure modified from Smith and Pimentel (2000).

The Mojave River ground-water basin has an area of about 3,600 km^2 (1,400 mi^2) and extends from the San Bernardino and the San Gabriel Mountains north, then northeastward to Afton Canyon (fig. 1). The basin is bounded by Antelope Valley to the west and shares its southeastern boundary with the Morongo ground-water basin near the town of Lucerne Valley. The Mojave River ground-water basin consists of several alluvial-filled valleys that are hydraulically connected. Streamflow in the Mojave River is the principal source of ground-water recharge to the Mojave River ground-water basin. Since July 1994, imported water has been released to the Mojave River southeast of Hesperia, which has resulted in additional recharge in the basin (Mojave Water Agency, 1996).

The Morongo ground-water basin has an area of about 2,600 km^2 (1,000 mi^2) and is bounded by the San Bernardino Mountains to the southwest, the Granite and the Ord Mountains to the northwest, the Bullion Mountains to the northeast, and the Little San Bernardino and the Pinto Mountains to the south (fig. 1). The ground-water basin is recharged by infiltration of streamflow from ephemeral stream channels, and more recently (1995), it has been recharged by artificial-recharge ponds constructed in the Yucca Valley area in 1995 (Smith and Pimentel, 2000).

GEOHYDROLOGY

Non-water-bearing consolidated igneous and metamorphic rocks underlie and surround the water-bearing unconsolidated deposits that compose the Mojave River and Morongo ground-water basins. Only the joints and fractures of the consolidated rocks contain water. The non-water-bearing rocks are not exposed in many areas of these basins but may form barriers to ground-water movement if they are present at altitudes higher than the water table (Mendez and Christensen, 1997).

The Mojave River and the Morongo ground-water basins are traversed by northwest to southeast right-lateral strike-slip faults (fig. 1) that, in many places, displace the aquifers (Smith and Pimentel, 2000). The fault planes generally are of low permeability and produce barriers or partial barriers to ground-water flow that result in abrupt changes in the water table across the fault (Londquist and Martin, 1991). The water table between the fault barriers is fairly flat in undeveloped areas; but in the developed areas, depressions have formed in the areas of substantial ground-water pumping and ground-water mounds have formed in areas of artificial recharge (Smith and Pimentel, 2000).

Mojave River Ground-Water Basin

The water-bearing deposits in the Mojave River ground-water basin are unconsolidated and partly consolidated alluvial material (Smith and Pimentel, 2000). The aquifer system in the Mojave River ground-water basin consists of two interconnected aquifers: a shallow alluvial flood-plain aquifer (Lines, 1996) and a regional aquifer (Hardt, 1971) underlying and surrounding the flood-plain aquifer. The flood-plain aquifer, which consists mainly of sand and gravel deposited by the Mojave River, is as much as 75 m (250 ft) thick. It generally increases in width from less than 35 m (120 ft) at the Upper Narrows to more than 8 km (5 mi) near Newberry Springs and is the most productive aquifer in the ground-water basin. The regional aquifer consists of unconsolidated older alluvium, fan deposits, and partly consolidated to unconsolidated sedimentary deposits as much as 1,220 m (4,000 ft) thick (Subsurface Surveys, 1990; Stamos and others, 2001). These deposits generally are fine grained, and their permeability decreases with depth (Stamos and Predmore, 1995; Smith and Pimentel, 2000). Perched ground-water conditions exist near El Mirage and Adelanto (Smith and Pimentel, 2000) (fig. 1). Perched ground water is unconfined ground water that is separated from an underlying aquifer by an unsaturated zone (Lohman, 1972).

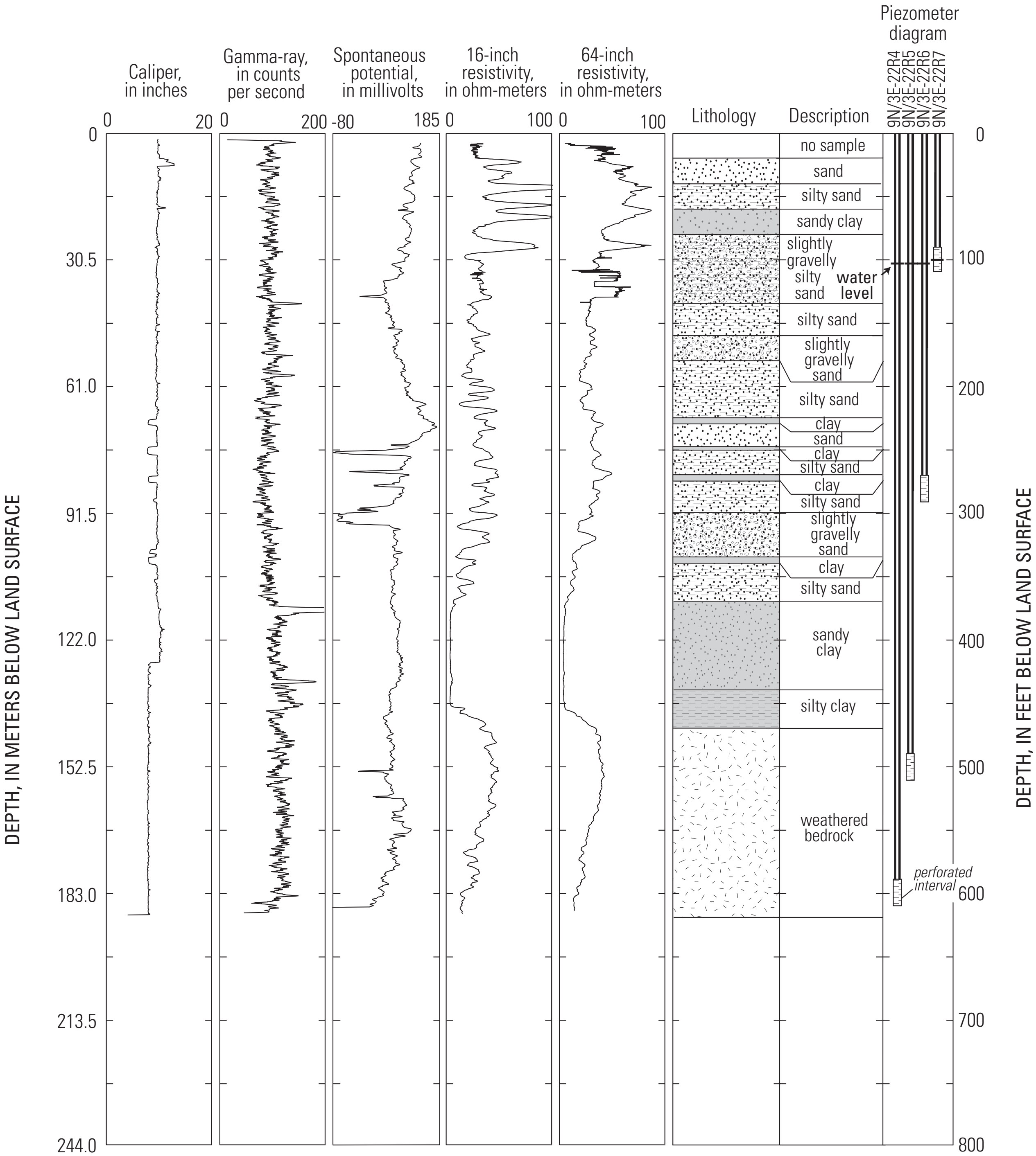


Figure 2. Geophysical and lithologic logs and construction diagrams of piezometers 9N/3E-22R4–7 in the Newberry Springs area of the Mojave River ground-water basin, San Bernardino County, California. Figure modified from Huff and others (2002). (See figure 11*A* for locations of piezometers and figure 12 for hydrographs.)

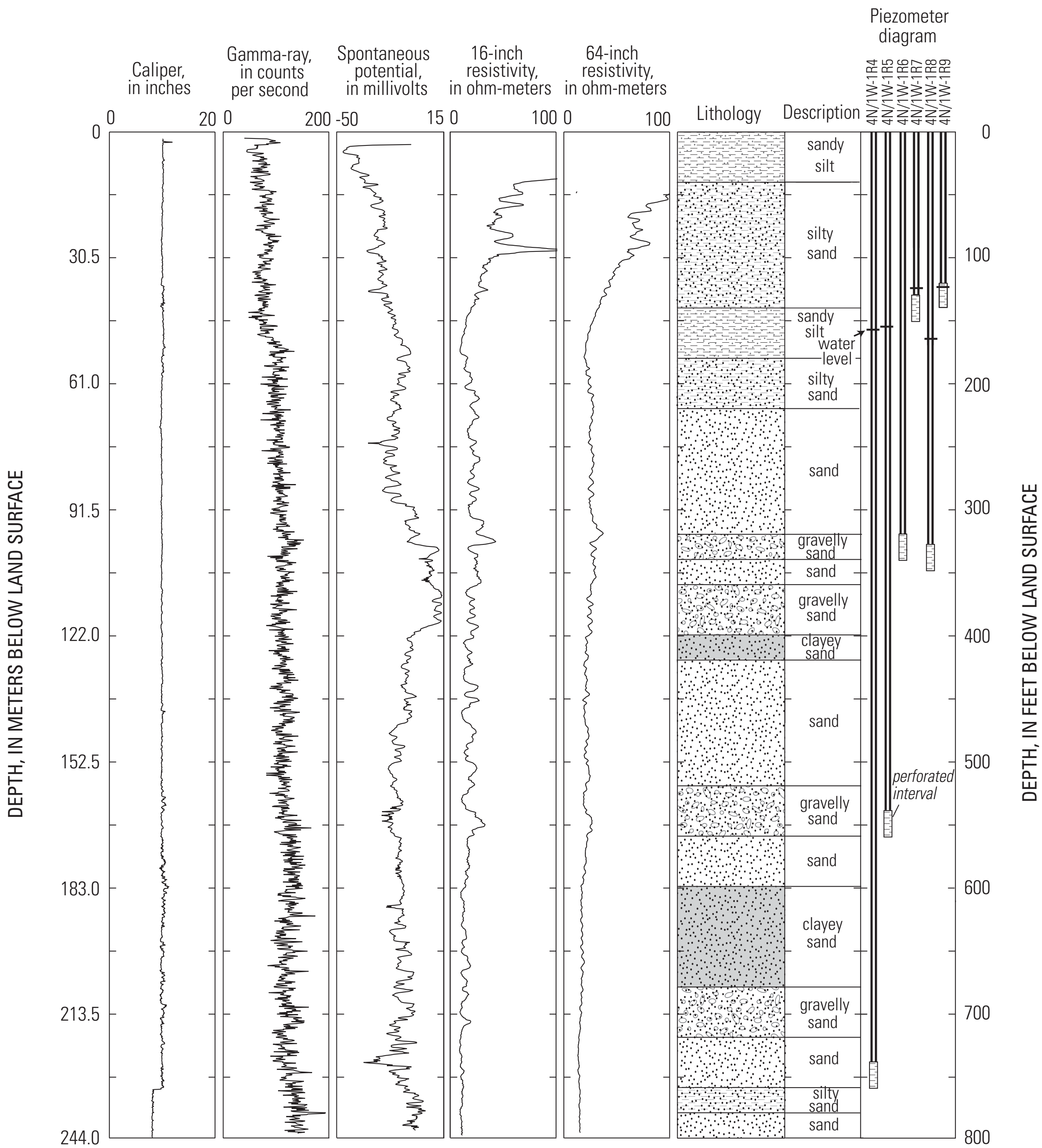


Figure 3. Geophysical and lithologic logs and construction diagrams of piezometers 4N/1W-1R4–9 in Lucerne Valley in the Morongo ground-water basin, San Bernardino County, California. Figure modified from Huff and others (2002). (See figure 13*A* for locations of piezometers and figure 14 for hydrographs.)

Three of the four areas discussed in this report—the El Mirage, Lockhart–Harper Lake (dry), and Newberry Springs areas—are in the Mojave River ground-water basin. The lithologic (driller) logs of four wells near El Mirage (wells 6N/6W-18L2, -18P4, -30M3, and 6N/7W-23J1) indicate an assemblage of alternating sand and clay with minor gravel, and clay-dominated sequences that range from about 30 m (100 ft) to nearly 60 m (200 ft) in thickness (see figure 7*A* in the section "El Mirage Area" for locations of wells). The maximum depth of these wells is 91 m (300 ft). The lithologic logs of five wells near Lockhart–Harper Lake (wells 11N/3W-8Z1, -28L4, -28L5, -28M1, and -28R5) indicate an assemblage of alternating sand and clay with minor gravel, and clay-dominated sequences that range from about 1.5 to 18 m (5 to 60 ft) in thickness [see figure 9*A* in the section "Lockhart–Harper Lake (dry) Area" for locations of wells]. The maximum depth of these wells is 340 m (1,117 ft). The lithologic log of well 11N/3W-8Z1 indicates nearly 76 m (250 ft) of clay, most of which is at depths greater than 260 m (850 ft). The lithologic and geophysical logs of the piezometers 9N/3E-22R4–7 at the multiple-completion monitoring site near Newberry Springs indicate a complex assemblage of clay, silt, and sand with minor gravel in the upper 143 m (470 ft) (see figure 11*A* in the "Newberry Springs Area" for location of monitoring site). The maximum depth of the piezometers is 186 m (610 ft). This assemblage includes a clay-dominated sequence at depths between about 113 and 143 m (370 and 470 ft) below land surface (fig. 2) (Julia Huff and others, 2002).

Morongo Ground-Water Basin

The water-bearing deposits in the Morongo ground-water basin consist of continental deposits of Quaternary and Tertiary ages that extend to a maximum depth of 3,050 m (10,000 ft) near the eastern edge of the basin (Moyle, 1984). In general, the continental deposits are unconsolidated at land surface and become partly consolidated with depth. The unconsolidated deposits form the most productive aquifer in the ground-water basin. Perched ground-water conditions exist in the Lucerne Valley area (Smith and Pimentel, 2000) (fig. 1).

Lucerne Valley, the fourth area discussed in this report, is in the Morongo ground-water basin. The geophysical and lithologic logs of the piezometers 4N/1W-1R4–9 at the multiple-completion monitoring site in Lucerne Valley, which has a maximum depth of 244 m (800 ft), indicate a complex assemblage of sand and silt with minor clay and gravel (see figure 13*A* in the section "Lucerne Valley Area" for location of monitoring site). The resistivity logs of this site indicate that permeability decreases with depth (fig. 3) (Huff and others, 2002).

MECHANICS OF LAND SUBSIDENCE

Land subsidence can occur in valleys containing aquifer systems that are, in part, made up of fine-grained sediments and that have undergone extensive ground-water development. The pore structure of a sedimentary aquifer system is supported by a combination of the granular skeleton of the aquifer system and the fluid pressure of the ground water that fills the intergranular pore space (Meinzer, 1928). When ground water is withdrawn in quantities that result in reduced pore-fluid pressures and water-level declines, more of the weight of the overlying sedimentary material must be supported by the skeleton. A loss of fluid-pressure support increases the intergranular load, or effective stress, on the skeleton. With a change in effective stress, the skeleton is subject to deformation—an increase in effective stress causes some degree of skeletal compression and a decrease causes expansion. The vertical component of this deformation sometimes results in irreversible compaction of the aquifer system and land subsidence. An aquifer-system skeleton that consists of primarily fine-grained sediments, such as silt and clay, is much more compressible than one that consists of primarily coarse-grained sediments, such as sand and gravel.

Aquifer-system deformation is elastic (recoverable) if the stress imposed on the skeleton is smaller than the previous maximum effective stress. The largest historical effective stress imposed on the aquifer system, sometimes the result of the lowest ground-water level, is called the "preconsolidation stress." When stresses are greater than the preconsolidation stress, the pore structure (granular framework) of the fine-grained sediments undergoes rearrangement toward a configuration that is more stable at higher stresses. This rearrangement results in an irreversible reduction of pore volume and, thus, in inelastic compaction of the aquifer system. Deformation under stresses in excess of the preconsolidation stress is 20 to more than 100 times greater than deformation under stresses less than the preconsolidation stress (Riley, 1998).

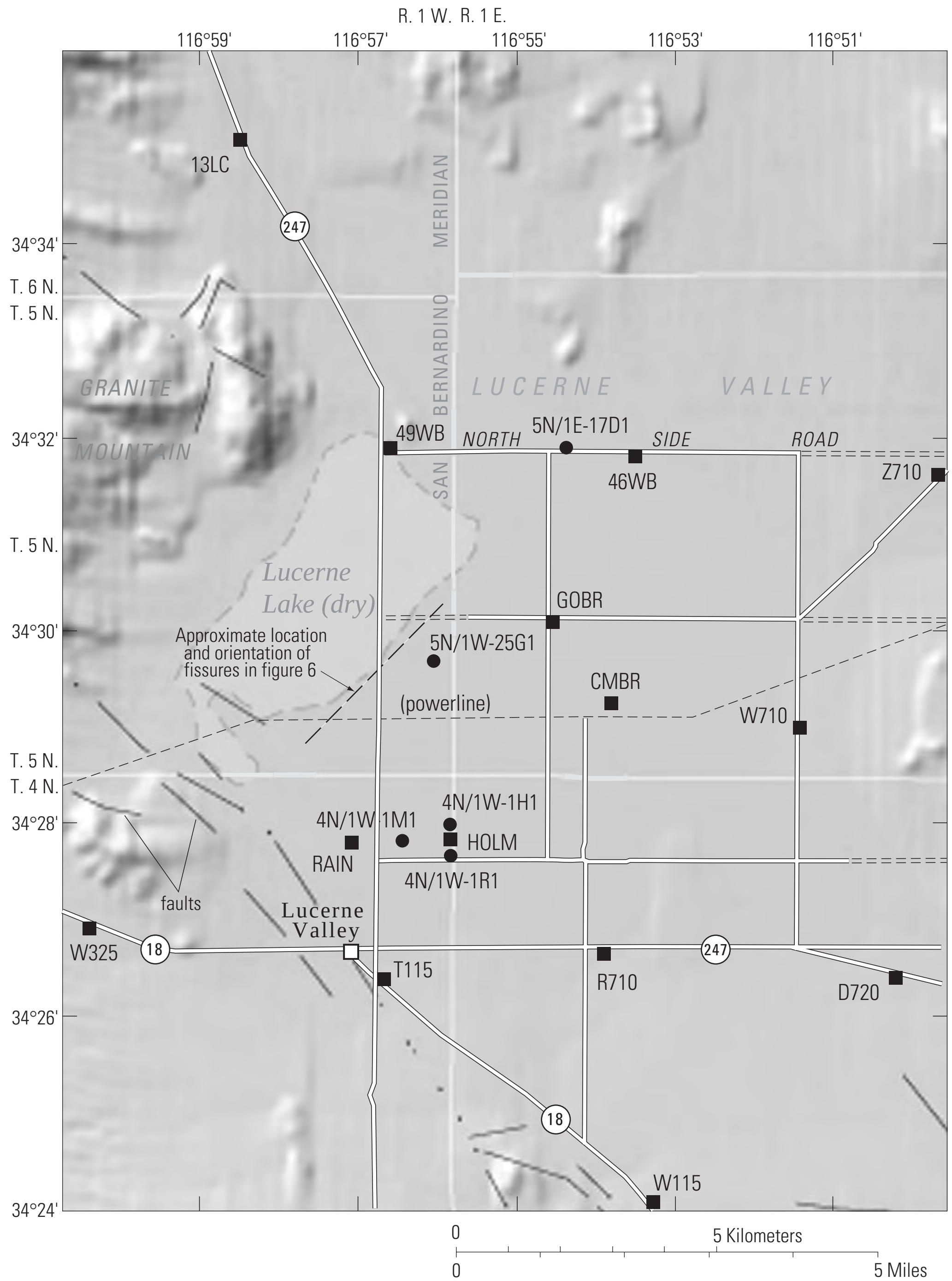
For an aquifer-system skeleton that has an appreciable thickness of fine-grained sediments, a significant part of the total compaction may be residual compaction (compaction that occurs in confining layers while heads in the confining layers equilibrate with heads in the adjacent aquifers). Depending on the thickness and the vertical hydraulic diffusivity of a confining layer, fluid-pressure equilibration—and thus compaction—lags behind pressure, or hydraulic head, declines in the adjacent aquifers; concomitant compaction may require decades or centuries to approach completion. The time required to attain about 93 percent of the total compaction after water levels have stabilized is referred to as the time constant (Riley, 1969). Ireland and others (1984) estimated that the time constants for aquifer systems at 15 sites in the San Joaquin Valley ranged from 5 to 1,350 years. Terzaghi (1925) described this delay in his theory of hydrodynamic consolidation. Numerical modeling based on Terzaghi's theory has successfully simulated complex histories of compaction caused by known water-level fluctuations (Helm, 1978; Hanson, 1989; Sneed and Galloway, 2000). For a more complete description of aquifer-system compaction, see Poland (1984), and for a review and selected case studies of land subsidence caused by aquifer-system compaction in the United States, see Galloway and others (1999).

GLOBAL POSITIONING SYSTEM (GPS) SURVEY OF LUCERNE VALLEY AREA

GPS is a U.S. Department of Defense satellite-based navigation system designed to provide continuous worldwide positioning and navigation capability. GPS surveying uses the satellite-based system with Earth-based reference stations to accurately determine the position (latitude and longitude) and the ellipsoid height (vertical coordinate) of geodetic monuments. In 1998, the USGS established a geodetic network in the Lucerne Valley to determine changes in land-surface elevations (land subsidence) at selected geodetic monuments by comparing GPS measurements made in 1998 with historical leveling measurements and to establish baseline values that can be used for comparisons with future monitoring measurements.

Land-Subsidence Monitoring Network

The land-subsidence monitoring network for this study consists of geodetic monuments used as GPS stations (fig. 4) at which horizontal and vertical positions can be measured accurately and repeatedly to determine changes in positions. Geodetic monuments are markers that are anchored in the ground or to a structure. For this study, historical data for the monuments in the Lucerne Valley were compiled and reviewed to determine the geographic extent and the quality of this data for use as vertical-control data. Because no monuments could be found in the area just southeast of Lucerne Lake (dry), an area where ground-water levels have declined about 30 m (100 ft) since about 1950 (fig. 5), four new monuments were installed—GOBAR, HOLMES, CAMBRIA, and RAINBOW (GPS stations GOBR, HOLM, CMBR, and RAIN, respectively). Historical land-surface elevations for these monuments were determined from spot elevations or interpolated from topographic contours on 7.5-minute topographic maps determined from aerial photography. The elevation for GOBAR is from the White Horse Mountain, California, 7.5-minute quadrangle developed from aerial photographs taken in 1975. The elevations for HOLMES, CAMBRIA, and RAINBOW are from the Lucerne Valley, California, 7.5-minute quadrangle developed from aerial photographs taken in 1969.



EXPLANATION

W115 ■ Global Positioning System (GPS) station and identifier

4N/1W-1R1 ● Well and identifier

Figure 4. Location of Global Positioning System (GPS) stations and wells used to monitor vertical changes in land surface and ground-water levels, respectively, in Lucerne Valley, San Bernardino County, California. (See figure 5 for hydrographs of wells).

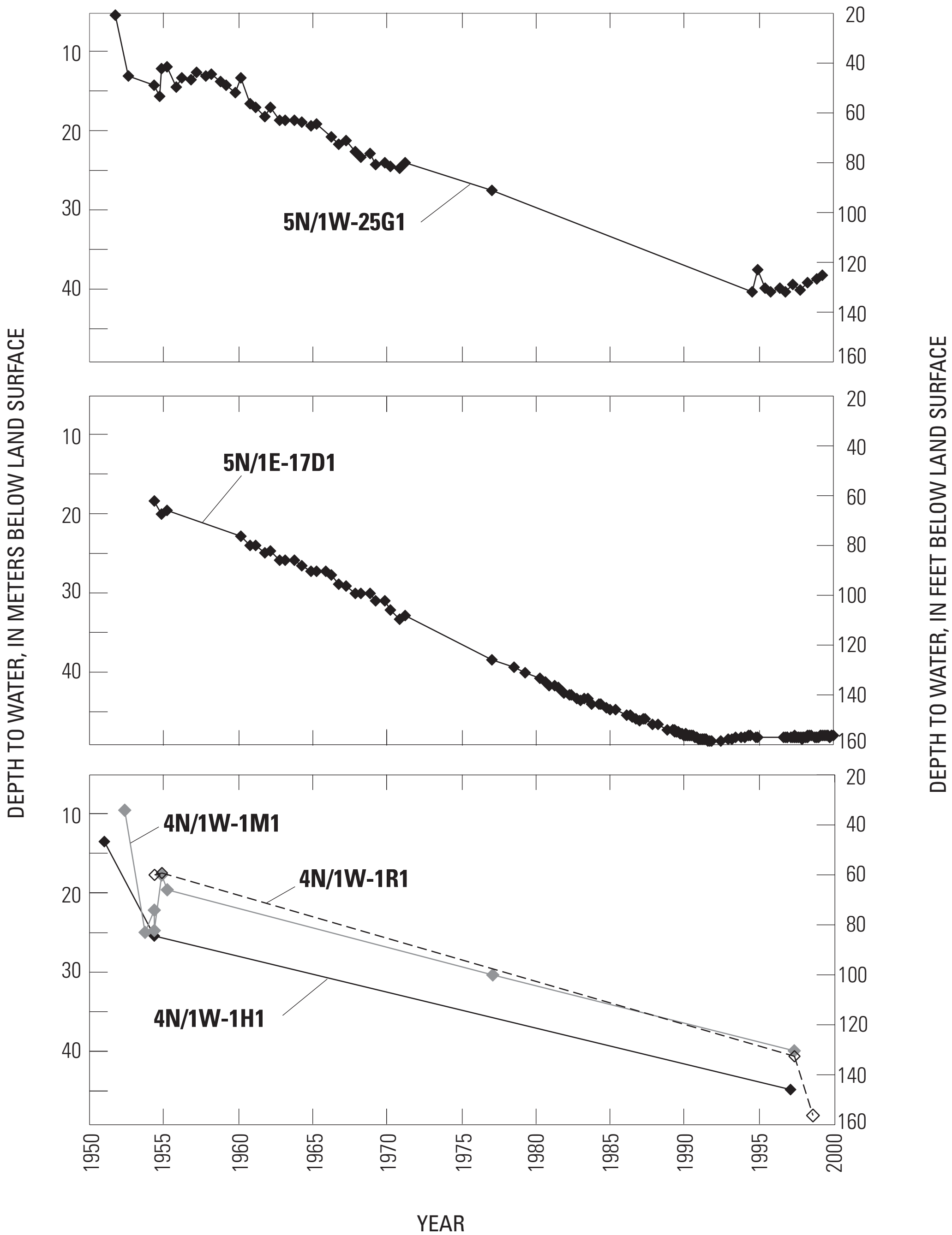


Figure 5. Depth to water for selected wells near Global Positioning System (GPS) stations in Lucerne Valley, San Bernardino County, California, where vertical changes were largest. (See figure 4 for locations of wells).

The land-subsidence monitoring network in the Lucerne Valley consists of 17 geodetic monuments (fig. 4; three of the monuments are located outside the area of figure 4; they are shown in figure 1). The spacing between the monuments met the generalized network design criterion established by Zilkoski and others (1997), which requires that the distance between local network points does not exceed 10 km (6 mi).

Determination of Ellipsoid Heights and Orthometric Heights (Elevations)

GPS measurements were made using five dual-frequency, full-wavelength P-code GPS receivers (Ashtech Z-XII) and choke-ring antennas (Dorne-Margolin) and three dual-frequency, full-wavelength GPS receivers (Trimble 4000SSi or 4000SSe) and compact L1/L2 antennas with ground planes. GPS measurements were made at the 17 GPS stations between June 17 and 19, 1998, to obtain ellipsoid heights and elevations (orthometric heights) (table 1). Ellipsoid height is the vertical coordinate relative to a geodetic reference system. The ellipsoid that closely approximates the Earth's shape in the study area is the North American Datum of 1983 (NAD83). Elevation is the vertical coordinate relative to a geodetic datum; the datum used in this report is the National Geodetic Vertical Datum of 1929 (NGVD29).

Table 1. Horizontal position, current (1998) ellipsoid and orthometric heights (elevations), historical elevations, and elevation change at geodetic monuments in the land-subsidence monitoring network in Lucerne Valley, San Bernardino County, California

[Location of Global Positioning System (GPS) stations shown in figures 1 and 4. Latitude and longitude are referenced to the North American Datum of 1983. Elevation is referenced to the National Geodetic Vertical Datum of 1929. Negative values for elevation change indicate subsidence. m, meter; ft, foot; mm, millimeter. —, no data]

GPS code name	Monument name	Latitude (1998)	Longitude (1998)	1998 ellipsoid height (m)	1998 orthometric height (elevation)		Historical elevation		Elevation change		Time period of elevation change
					(m)	(ft)	(m)	(ft)	(mm)	(ft)	
0804 [1,2]	HPGN 08-4 GPS-SOAP 1990	34°54′14″	116°58′51″	662.050	—	—	—	—	—	—	—
HECT [1,2]	HECTOR 2 1966	34°47′06″	116°25′15″	598.370	—	—	—	—	—	—	—
13LC	13 LC 1953	34°35′12″	116°58′28″	901.778	932.89	3,060.66	[3]932.86	[3]3,060.57	[4]30	[4]0.1	1976–98
49WB	49 WBC 1976	34°31′52″	116°56′42″	836.935	868.05	2,847.93	[3]868.16	[3]2,848.31	[4]–120	[4]–.4	1976–98
46WB	46 WBC 1976	34°31′52″	116°53′34″	855.291	886.36	2,908.02	[3]886.36	[3]2,908.01	fixed	fixed	1976–98
Z710	Z 710 1944	34°31′35″	116°49′40″	907.638	938.66	3,079.59	[3]938.70	[3]3,079.72	[4]–30	[4]–.1	1944–98
GOBR	GOBAR	34°30′08″	116°54′38″	839.442	870.52	2,856.04	[5]871.1	[5]2,858	[4]–600	[4]–2	1976–98
CMBR	CAMBRIA	34°29′13″	116°53′51″	843.659	874.71	2,869.78	[5]874.8	[5]2,870	[4]0	[4]0	1976–98
W710	W 710 1944	34°28′56″	116°51′28″	856.756	887.78	2,912.66	[3]887.84	[3]2,912.86	[4]–60	[4]–.2	1944–98
RAIN	RAINBOW	34°27′44″	116°57′01″	841.976	873.03	2,864.27	[5]873.6	[5]2,866	[4]–600	[4]–2	1976–98
HOLM	HOLMES	34°27′38″	116°55′42″	845.095	876.12	2,874.41	[5]876.6	[5]2,876	[4]–600	[4]–2	1976–98
W325 [1]	W 325 RESET 1958	34°26′57″	117°00′08″	870.932	902.02	2,959.37	[3]902.02	[3]2,959.37	fixed	fixed	1993–98
R710	R 710 1944	34°26′38″	116°53′56″	870.922	901.87	2,958.89	[3]901.91	[3]2,959.01	[4]–30	[4]–.1	1993–98
D720	D 720 1944	34°26′23″	116°50′28″	879.640	910.56	2,987.39	[3]910.56	[3]2,987.39	fixed	fixed	1993–98
T115	T 1152 1961	34°26′02″	116°56′14″	892.822	923.76	3,030.71	[3]923.76	[3]3,030.71	[4]0	[4]0	1961–98
W115	W 1152 1961	34°24′04″	116°53′25″	974.110	1,004.80	3,296.60	[3]1,004.80	[3]3,296.60	fixed	fixed	1961–98
LAZY [1,2]	LAZY 1980	34°20′38″	116°30′50″	1,028.220	—	—	—	—	—	—	—

[1]Network control station.

[2]High Precision Geodetic Network (HPGN) station.

[3]Determined from historical leveling measurements.

[4]Values are within measurement error.

[5]Estimated by interpolating elevation values from 3-m (10-ft) topographic contours. Elevation changes computed using these estimated elevations have a 1,500 mm (5-ft) uncertainty.

GPS surveying was done in accordance with version 4.3 of “Guidelines for Establishing GPS-Derived Ellipsoid Height” by Zilkoski and others (1997). GPS measurements were made at 13 of the 17 GPS stations on at least 2 days, and data were recorded during 50-minute observation periods. GPS measurements were made at the other four GPS stations—the network control stations—on all 3 days of the GPS survey, and data were recorded during 5.5-hour observation periods. Three of the four network control stations—HPGN 08-4 GPS-SOAP 1990, HECTOR 2 1966, and LAZY 1980 [0804, HECT, and LAZY, respectively (fig. 1)]—are part of the statewide High Precision Geodetic Network (HPGN); the fourth network control station, W325 RESET 1958 (W325) (fig. 4) is not. The network control stations were selected on the basis of their vertical stability and geographic distribution; these stations are located at the perimeter of the land-subsidence monitoring network (fig. 1) and in areas where little ground-water pumping occurs and vertical land-surface changes were assumed small. The only variation in the way the GPS surveys were conducted for this study from that in the guidelines of Zilkoski and others (1997) was that single-baseline, rather than multi-baseline, processing software was used for postprocessing. There are no known conclusive tests that permit an objective evaluation of the effect of using single-baseline, rather than multi-baseline, processing software (Craymer and Beck, 1992) and, therefore, the single-baseline software was used because it was readily available. GPSurvey version 2.30 (Trimble) was used for the baseline and relative-positioning computations.

The orthometric heights (elevations) of 14 of the GPS stations in the network were determined during two phases of relative positioning. During the first phase, the horizontal coordinates and ellipsoid heights of three of the network control stations (the three HPGN stations) were held fixed to calculate the horizontal coordinates and ellipsoid heights of the fourth network control station, W325, and network station GOBR. GOBR was selected for determination of ellipsoid heights during the first phase of relative positioning because several surveying measurements had been made at this station and because it was not adjacent to W325 (fig. 4). During the second phase, the elevations of GPS stations 46WB, D720, W115, and W325 were obtained from National Geodetic Survey (NGS) data sheets. The elevations of these four stations and the horizontal coordinates for W325 and GOBR, determined during the first phase, were held fixed, and the horizontal positions and elevations (derived from ellipsoid heights determined using modeled geoid separations of GEOID96) were calculated for the other 10 GPS stations (table 1).

GPS Results and Ground-Water Levels in Nearby Wells

The elevations of the GPS stations determined from the 1998 GPS survey were compared with historical elevations that had been determined either by leveling or by estimating the historical elevations of the GPS stations. Ground-water-level data for areas indicated as having possible subsidence were analyzed to determine if they were near areas that had large ground-water-level declines. The historical elevations for GPS stations GOBR, HOLM, CMBR, and RAIN were estimated by interpolating elevations from topographic contours determined from aerial photographs taken in 1975 (GOBR) and in 1969 (HOLM, CMBR, and RAIN). Using elevations determined from topographic contours to calculate land subsidence incorporates an error of as much as 1,500 mm (5 ft). The historical land-surface elevations, which were estimated from the 1969 and 1975 topographic contour maps were compared with elevations determined from the 1998 GPS survey. Results of the comparison indicate that about 600 mm (2 ft) of subsidence occurred at GPS stations GOBR, HOLM, and RAIN for the two periods of comparison (1969–98 and 1975–98), but these results are essentially nullified by the 1,500 mm (5 ft) error associated with estimating the historical elevations (table 1). These stations are in the center of the GPS network, southeast of Lucerne Lake. The historical land-surface elevations for the remaining stations were determined from historical leveling measurements (made as early as 1944 at some stations). Results of that comparison indicated that little or no change had occurred at these stations since the historical leveling measurements were made (table 1).

A

B

Figure 6. Fissures near Lucerne Lake (dry) in San Bernardino County, Mojave Desert, California. ***A***, View to the southwest, with 5-gallon bucket for scale. ***B***, View to the northeast, with 5-gallon bucket for scale. See figure 4 for approximate location and orientation. Photographs taken in May 2001 by Loren Metzger, U.S. Geological Survey.

Inspection of the southern Lucerne Lake (dry) area in May 2001 revealed fissures trending northeast/southwest across State Route 247 (fig. 4). In some instances, the fissures were more than 1 m (3.3 ft) in width and in depth (fig. 6); the fissures probably have enlarged as a result of erosion. Fissuring often is associated with localized differential compaction of unconsolidated sediment. Fissures formed by this mechanism are caused by the stretching of the aquifer-system structure owing to the bending of the overlying sediment of the differentially compacting zone (Holzer, 1984). The orientation of the fissures is consistent with subsidence to the northwest or southeast. Because bedrock crops out at land surface to the northwest (Granite Mountains), which indicates a small thickness of unconsolidated sediment, the most likely area of subsidence is to the southeast where unconsolidated sediment thickens. The GPS monitoring network is located in this area of possible subsidence.

The ellipsoid heights of the GPS stations determined for 1998 will serve as baseline measurements that can be used for comparisons with measurements from future surveys. Errors resulting from comparisons of ellipsoid heights from this study with those determined during future studies may be as small as plus or minus (±) 20 mm (± 0.07 ft) because errors associated with orthometric-height control stations, as well as those associated with modeled geoid separations that convert the ellipsoid heights to orthometric heights, will become irrelevant.

GPS measurements for the GPS stations in the monitoring network indicate that subsidence may have occurred at three stations—GOBR, HOLM, and RAIN (fig. 4). About 600 mm (2 ft) ± 1,500 mm (±5 ft) of subsidence occurred at GOBR between 1975 and 1998 and at HOLM and RAIN between 1969 and 1998. Between 1977 and 1998, water levels declined about 11 m (36 ft) in well 5N/1W-25G1, which is about 2.1 km (1.3 mi) southwest of GOBR, and about 10 m (33 ft) in well 5N/1E-17D1, which is about 3.2 km (2 mi) north of GOBR (figs. 4 and 5). The screened intervals of these wells are unknown, but well 5N/1E-17D1 is only about 52 m (170 ft) deep. Water levels declined about 9 m (30 ft) in well 4N/1W-1M1 [screened interval 11 to 102 m (36 to 336 ft) below land surface] between 1977 and 1997; this well is near HOLM and RAIN (figs. 4 and 5). Only three water-level measurements were available for wells 4N/1W-1R1 and -1H1, near HOLM and RAIN, for the period between 1954 and the late 1990s. The measurements for well 4N/1W-1R1 for 1954 and 1998 and for well 4N/1W-1H1 for 1954 and 1997 indicate that water levels declined about 29 and 19 m (95 and 62 ft), respectively (fig. 5). The screened interval of well 4N/1W-1R1 is unknown, but the screened interval of well 4N/1W-1H1 is 76 to 119 m (250 to 390 ft) below land surface.

During the 1990s, the water-level measurements for these wells were near or lower than the previously recorded low levels for these wells (Trayler and Koczot, 1995; Smith and Pimentel, 2000) (fig. 5). The relation between subsidence and the record low water levels in the wells in the central part of the GPS network suggests that the preconsolidation stress of the aquifer system may have been exceeded during the 1969–98 and 1975–98 periods and that compaction may be permanent in these areas.

INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR)

InSAR Methods

InSAR is a powerful technique that uses differences in reflected radar signals acquired at different times to measure ground-surface deformation. This technique has been used to investigate deformation resulting from earthquakes (Massonnet and others, 1993), volcanoes (Massonnet and others, 1995), and land subsidence (Massonnet and others, 1997; Fielding and others, 1998; Galloway and others, 1998; Amelung and others, 1999; Hoffmann and others, 2001; Sneed and others, 2001). Twenty-four interferograms with temporal baselines ranging from 3 to 41 months were developed for this study using 14 synthetic aperture radar (SAR) scenes acquired by European Earth Remote-Sensing (ERS) satellites. Five interferograms were developed for the El Mirage area, six for the Lockhart–Harper Lake (dry) area, six for the Newberry Springs area, and seven for the Lucerne Valley area. Each interferogram was produced by combining two SAR scenes that had nearly identical acquisition geometries to form a “change” interferogram. The amplitude component of the change interferogram shows the intensity of the radar backscatter and reveals features of the land surface, such as mountains, roads, drainage ways, and engineered structures. The phase component of the change interferogram contains information about the coherent displacements imaged by radar and about the topography. The topographic component was removed using an interferogram produced from SAR scenes acquired on 2 successive days (tandum interferogram).

For landscapes that have more or less stable radar reflectors (such as buildings or other engineered structures, or undisturbed rocks and ground surfaces) over a period of time, it is possible to make high-precision measurements of changes in position or displacements of the reflectors caused by deforming aquifer systems (Galloway and others, 2000). Displacements are calculated from a phase change at each point in the interferogram. The phase change is determined by differencing or “interfering” two radar scans made of the same area at different times (Galloway and others, 2000).

Because the phase of the radar echo is proportional to the distance traveled by the pulse, any motion of the ground surface that occurs between two SAR scenes causes a phase difference in the interferogram. Phase differences can also be caused by propagation delays of the radar signal, such as delays caused by the variable water vapor in the atmosphere, also known as atmospheric artifacts (Zebker and others, 1997). Phase differences caused by propagation delays and not by deformation of the land surface can be identified using independent interferograms. Independent interferograms are interferograms that do not share a common SAR scene. For this study, if a particular signal—for example an indication of an area of subsidence—was evident in only one interferogram or in multiple interferograms that shared a common SAR scene, that signal was attributed to a propagation delay in the shared SAR scene rather than to deformation of the land surface. Because atmospheric artifacts were not evident in the change interferograms, except where noted, the coherent phase differences were attributed to range displacements of the ground surface, which were assumed vertical.

On the phase images, an area of coherent displacements, for example an area of subsidence, is shown by color fringes that define a shape; more color fringes indicate more change. For the interferograms in this report, one color cycle, for example blue to blue, indicates 28 mm (0.09 ft) of range displacement or change. The direction of change—subsidence or uplift—is indicated by the color progression of the fringes toward the center of the shape. The color-fringe progression of red-orange-yellow-green-blue-purple indicates subsidence; the opposite progression indicates uplift.

InSAR cannot be used to make high-precision measurements over fairly long time periods for landscapes that lack substantial stable radar reflectors; such landscapes include agricultural land where farming practices disturb the ground surface or dry lake beds where episodic flooding occurs. The phase image of such landscapes will show an incoherent speckled pattern rather than coherent color fringes; this speckled pattern indicates decorrelation. Developing images for shorter temporal baselines often will increase image coherency because there generally will be less disturbance during shorter time periods.

The phase component of the interferograms presented in this report was "unwrapped" to construct the displacement profiles, or cross sections, of the interferograms. Unwrapping of the phase component was done using a "branch cut" approach developed by Goldstein and others (1988). This approach is discussed in detail in Rosen and others (2000). The locations of the cross sections of the coherent interferograms were selected using a set of interferograms for each area of interest (for example, a set of five interferograms were used for the El Mirage area), and, therefore, the cross sections do not always intersect the areas of maximum subsidence in some of the interferograms. Cross sections of the fairly incoherent interferograms are not included in this report.

All the features that indicate subsidence on the interferograms are not discussed in this report. Reasons for omitting these features from the discussion are (1) the feature is not evident in independent interferograms, (2) the feature is suspect owing to its proximity to mountains, (3) the feature is poorly correlated, and (4) the feature is small in magnitude and (or) spatial distribution.

InSAR Results

InSAR results are presented for the El Mirage, Lockhart-Harper Lake (dry), and Newberry Springs areas in the Mojave River ground-water basin and for the Lucerne Valley area in the Morongo ground-water basin. Available ground-water-level data for areas undergoing vertical land-surface changes were examined to determine whether the vertical land-surface changes may be related to aquifer-system deformation caused by ground-water-level changes. More often than not, the water-level data were insufficient for determining if deformation was related to the water-level changes. Additional water-level measurements, perhaps made as frequently as seasonally, from depth-dependent or aquifer-dependent wells are needed to determine if the land-surface deformations evident in the interferograms are related to changes in water levels.

Mojave River Ground-Water Basin

El Mirage Area

Five interferograms were developed for the El Mirage area between April 1995 and November 1999; they have temporal baselines of 5, 6, 12, 16, and 21 months (fig. 7). Four of the five interferograms—the interferograms that have adjacent temporal baselines of 12 months [April 21, 1995, to April 6, 1996 (fig. 7*B*)]; 16 months [April 6, 1996, to August 9, 1997 (fig. 7*D*)]; 21 months [August 9, 1997, to May 1, 1999 (fig. 7*E*)]; and 6 months [May 1, 1999, to November 27, 1999 (fig. 7*F*)]—compose time series 1 in figure 8. The fifth interferogram, which spans 5 months [April 6, 1996, to September 28, 1996 (fig. 7*C*)] is a temporal subset of the 16-month interferogram (fig. 7*D*) and composes the single interferogram in figure 8. Although the approximately 100-km^2 radar scene includes parts of Antelope Valley where subsidence is occurring, only the El Mirage area of this radar scene is discussed in this report. For a detailed discussion of subsidence in Antelope Valley, see Galloway and others (1998).

All five interferograms show a subsidence pattern south of the southeastern tip of El Mirage Lake (dry). The persistent pattern indicates three areas of subsidence that together form an approximate L shape—the long limb is about 5 km (3.1 mi) north to south along the cross-section line V1–V1′, and the short limb is about 2.5 km (1.6 mi) west to east along the cross-section line H2–H2′. The 12-, 5-, and 16-month interferograms (fig. 7*B*, *C*, and *D*, respectively) show this pattern best; the 21-month interferogram (fig. 7*E*) is not as coherent (although the pattern is still evident), and the 6-month interferogram (fig. 7*F*) shows almost no subsidence. The interferograms for the El Mirage area indicate that three areas subsided as much as 50 mm (0.16 ft) cumulatively during the 48-month period between April 21, 1995, and May 1, 1999, and that very little vertical change occurred during the 6-month period between May 1, 1999, and November 27, 1999 (figs. 7 and 8).

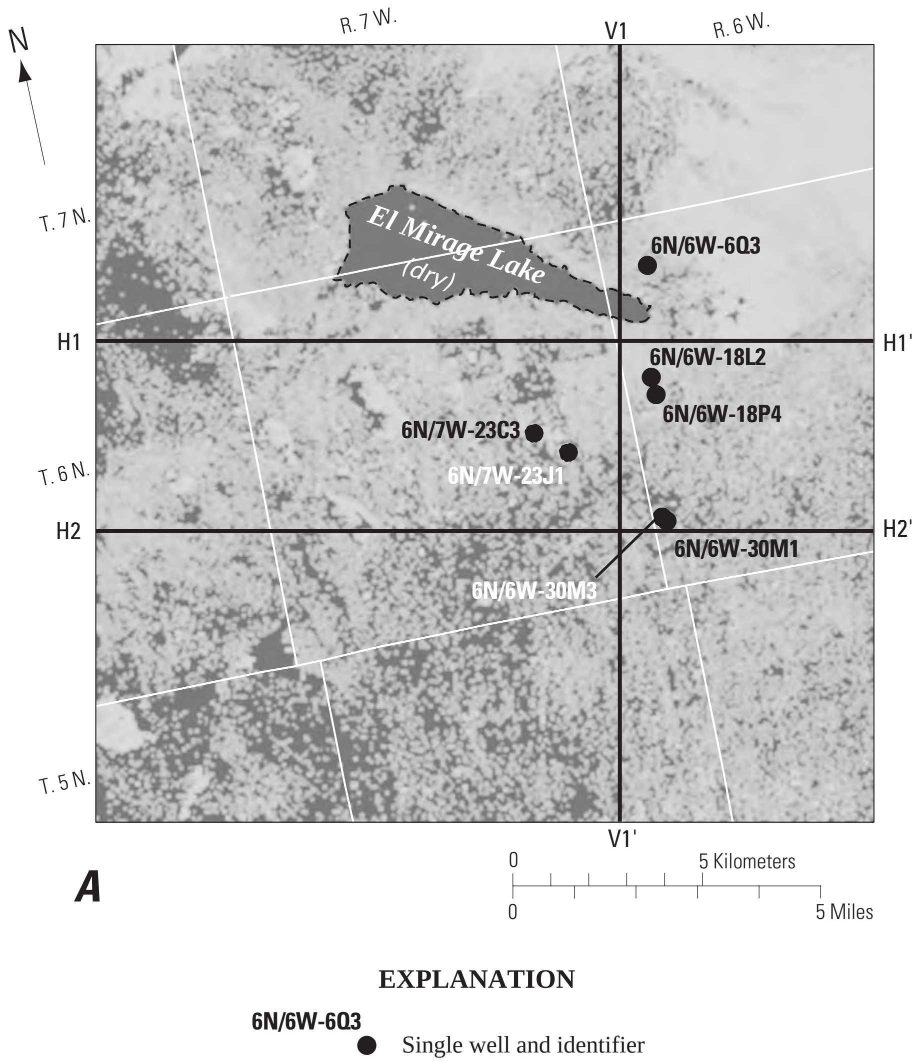
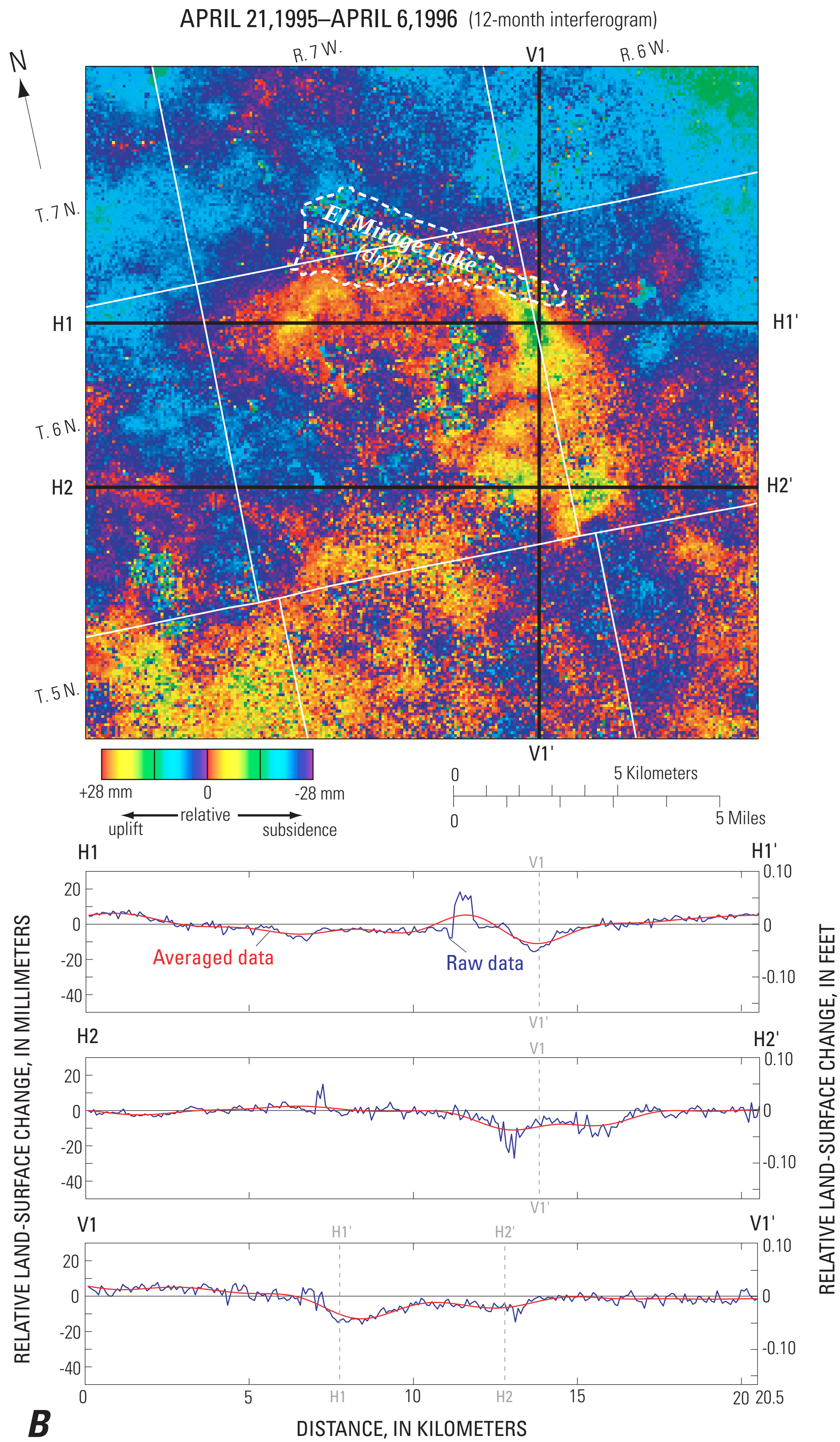


Figure 7. Amplitude image showing land-surface features and locations of wells used to evaluate subsurface geology or to monitor ground-water levels, and phase images and graphs showing vertical land-surface changes in the El Mirage area, San Bernardino County, California. Amplitude image (***A***) and phase images and graphs showing land-surface change for (***B***) April 21, 1995, to April 6, 1996; (***C***) April 6, 1996, to September 28, 1996; (***D***) April 6, 1996, to August 9, 1997; (***E***) August 9, 1997, to May 1, 1999; and (***F***) May 1, 1999, to November 27, 1999. (See figure 1 for location of area; see figure 8 for hydrographs of selected wells.)



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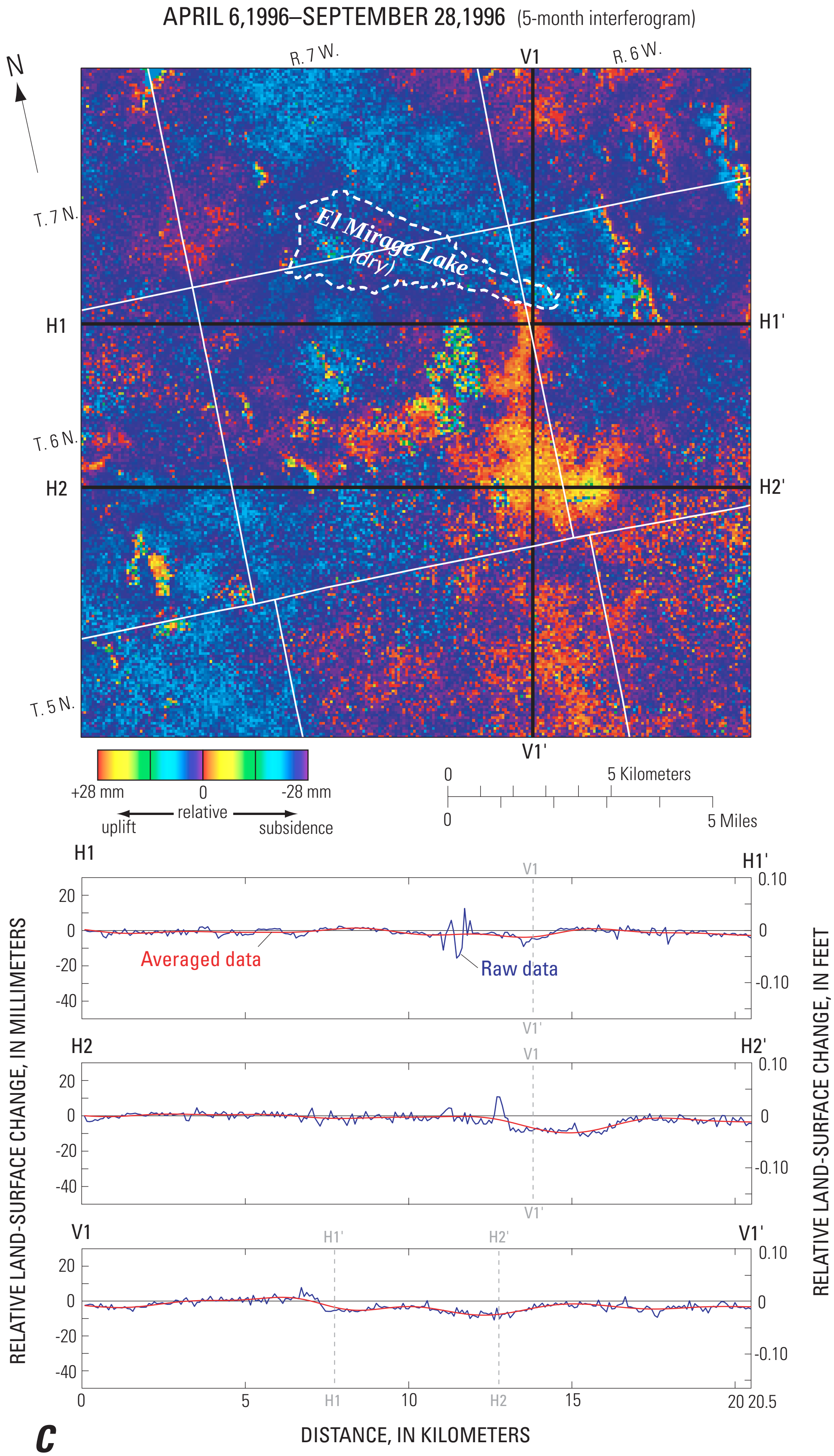

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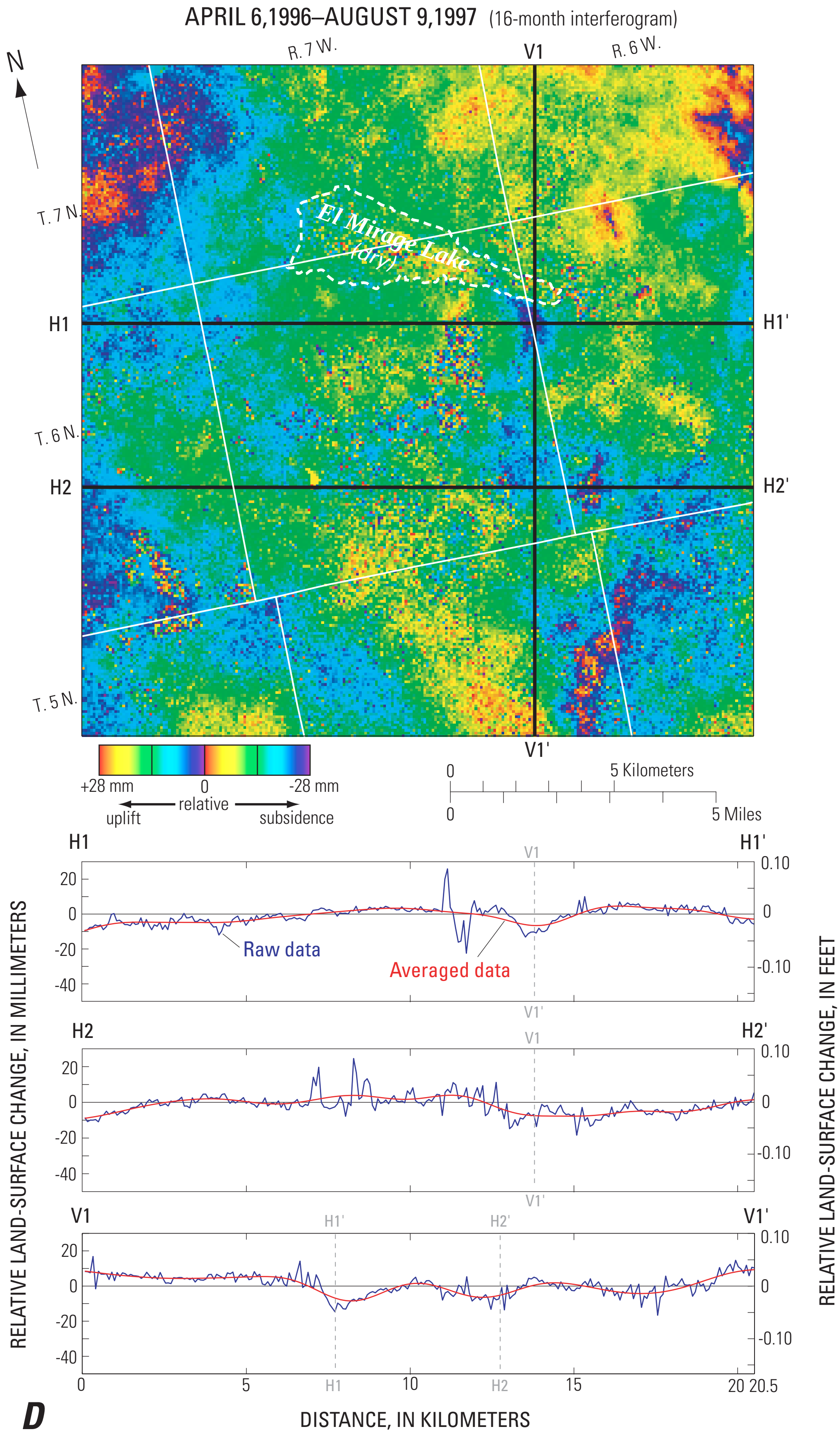

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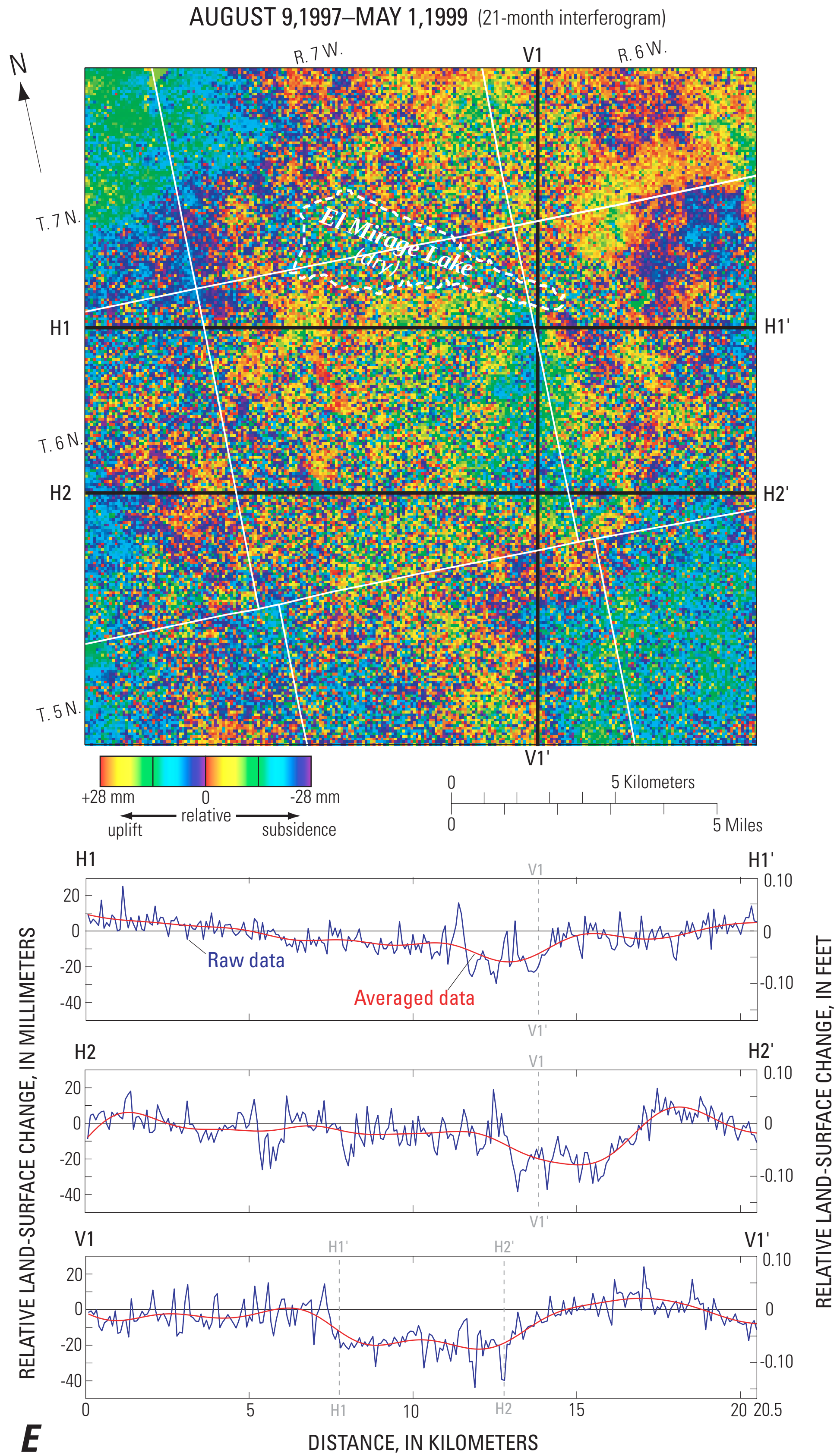

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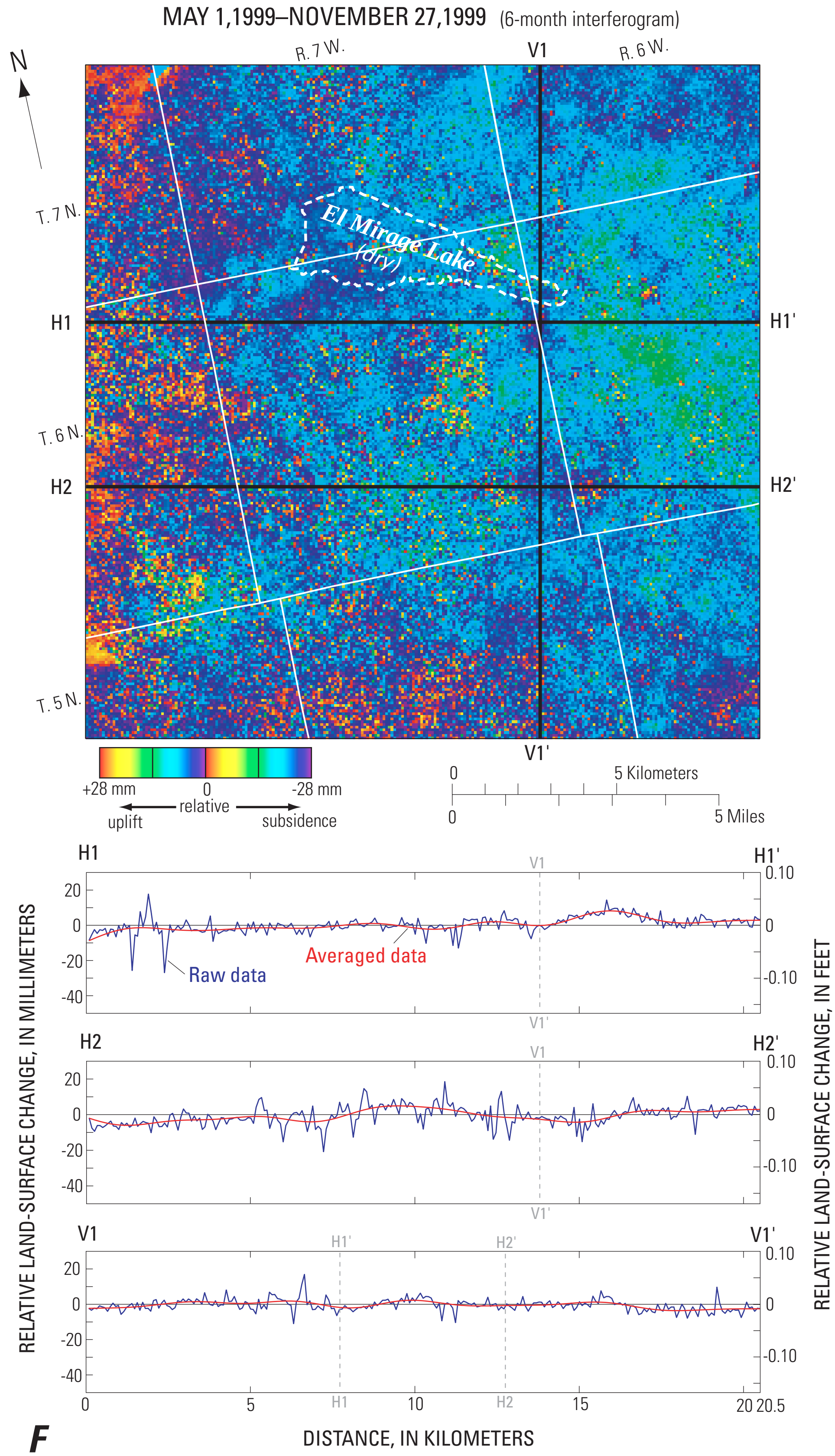

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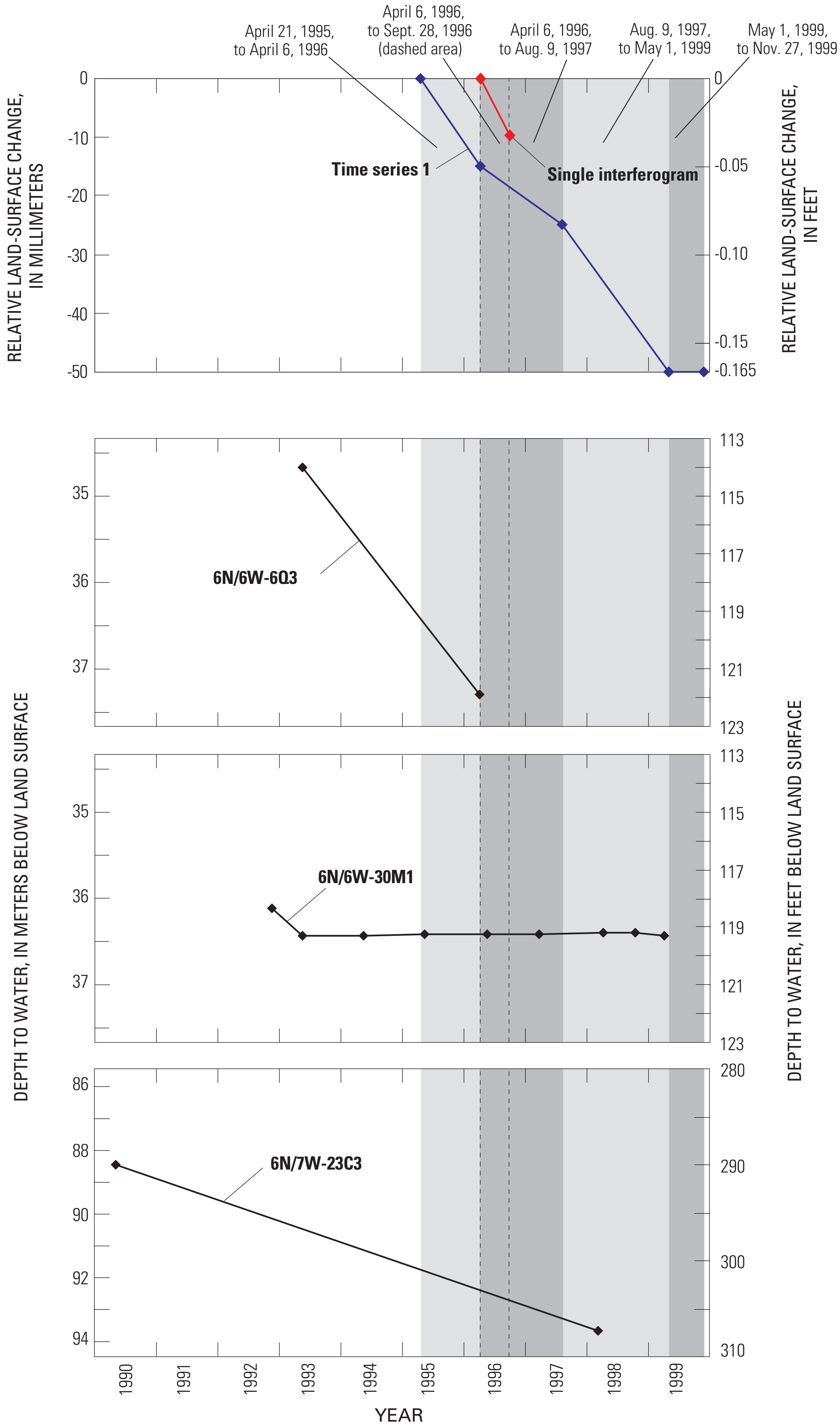


Figure 8. Depth to water for selected wells and relative land-surface change in the El Mirage area, San Bernardino County, California. (See figure 7*A* for locations of wells.)

Ground-water level data were examined for wells near El Mirage Lake (dry), an area where the interferograms show that as much as 50 mm (0.16 ft) of subsidence occurred south of the southeastern tip of El Mirage Lake (dry) during 1995–99 (fig. 8). Water-level data are sparse for this period; only three wells near the subsiding area had temporally relevant data. Two wells—6N/6W-6Q3 and -30M1—are screened in the perched zone (Smith and Pimentel, 2000). Well 6N/6W-6Q3 is just north of the southeastern tip of El Mirage Lake (fig. 7*A*). Only two water-level measurements were made at well 6N/6W-6Q3; these measurements indicate a water-level decline of about 2.4 m (8 ft) between the spring of 1993 and the spring of 1996 (fig. 8). Well 6N/6W-30M1 is about 5.5 km (3.4 mi) south of the southeastern tip of El Mirage Lake (dry) (fig. 7*A*). At least one water-level measurement was made at this well each spring between 1992 and 1999; these measurements indicate that water levels were stable, declining less than 0.3 m (1 ft) (fig. 8). Well 6N/7W-23C3 is screened 85 to 213 m (280 to 700 ft) below land surface in the regional aquifer about 4 km (2.5 mi) south of El Mirage Lake (dry) and about 3.7 km (2.3 mi) northwest of well 6N/6W-30M1 (fig. 7*A*). The two available water-level measurements for this well indicate a water-level decline of about 5.2 m (17 ft) between the spring of 1990 and the spring of 1998 (fig. 8). Much of this decline may have occurred between the spring of 1990 and the spring of 1993, before the adjudication began that resulted in decreased pumpage (Stamos and others, 2001). (The adjudication of the Mojave Basin area was the legal process that allocated the right to produce water from the available natural water supply. Until the Mojave Water Agency initiated the adjudication and an independent court issued the judgement, water production rights and obligations had never been defined in the Mojave Basin. The court's final decision was reached in January 1996.) The location of well 6N/7W-23C3 is nearly coincident with the water-level depression indicated by the 1998 water-level contours reported by Smith and Pimentel (2000). Ground-water flow simulations of the Mojave River ground-water basin show that water levels declined as much as 53 m (175 ft) south of El Mirage Lake (dry) between the late 1950s and 1999 (Stamos and others, 2001). The water-level declines in the regional aquifer indicated by recent measurements in well 6N/7W-23C3 and simulations for historical periods may have been large enough to cause the measured subsidence

Lockhart–Harper Lake (Dry) Area

Six interferograms were produced for the Lockhart–Harper Lake (dry) area. The interferograms compose two temporally overlapping time-series maps of vertical land-surface deformation. The six interferograms have temporal baselines of 3, 5, 8, 14, 24, and 41 months for the period April 1992 to November 1999 (fig. 9). The 14-month [April 24, 1992, to June 18, 1993 (fig. 9*B*)], 24-month [June 18, 1993, to June 11, 1995 (fig. 9*C*)], 3-month [June 11, 1995, to September 24, 1995 (fig. 9*D*)], and 8-month [September 24, 1995, to May 26, 1996 (fig. 9*E*)] interferograms form time series 1 in figure 10; the 41-month [January 8, 1996, to June 21, 1999 (fig. 9*F*)] and the 5-month [June 21, 1999, to November 8, 1999 (fig. 9*G*)] interferograms form time series 2 in figure 10. Three of the six interferograms, the 14-month [April 24, 1992, to June 18, 1993 (fig. 9*B*)], 24-month [June 18, 1993, to June 11, 1995 (fig. 9*C*)], and 41-month [January 8, 1996, to June 21, 1999 (fig. 9*F*)] clearly show a deformation pattern on the northeastern shore of Harper Lake (dry). The 3-month [June 11, 1995, to September 24, 1995 (fig. 9*D*)], 8-month [September 24, 1995, to May 26, 1996 (fig. 9*E*)], and 5-month [June 21, 1999, to November 8, 1999 (fig. 9*G*)] interferograms do not show this pattern clearly. At least two of the six interferograms for the Lockhart–Harper Lake (dry) area—the 3-month (June 11, 1995, to September 24, 1995) and the 5-month (June 21, 1999, to November 8, 1999) interferograms—show atmospheric artifacts (fig. 9*D* and *G*, respectively) that may have affected the interpretations of vertical land-surface changes.

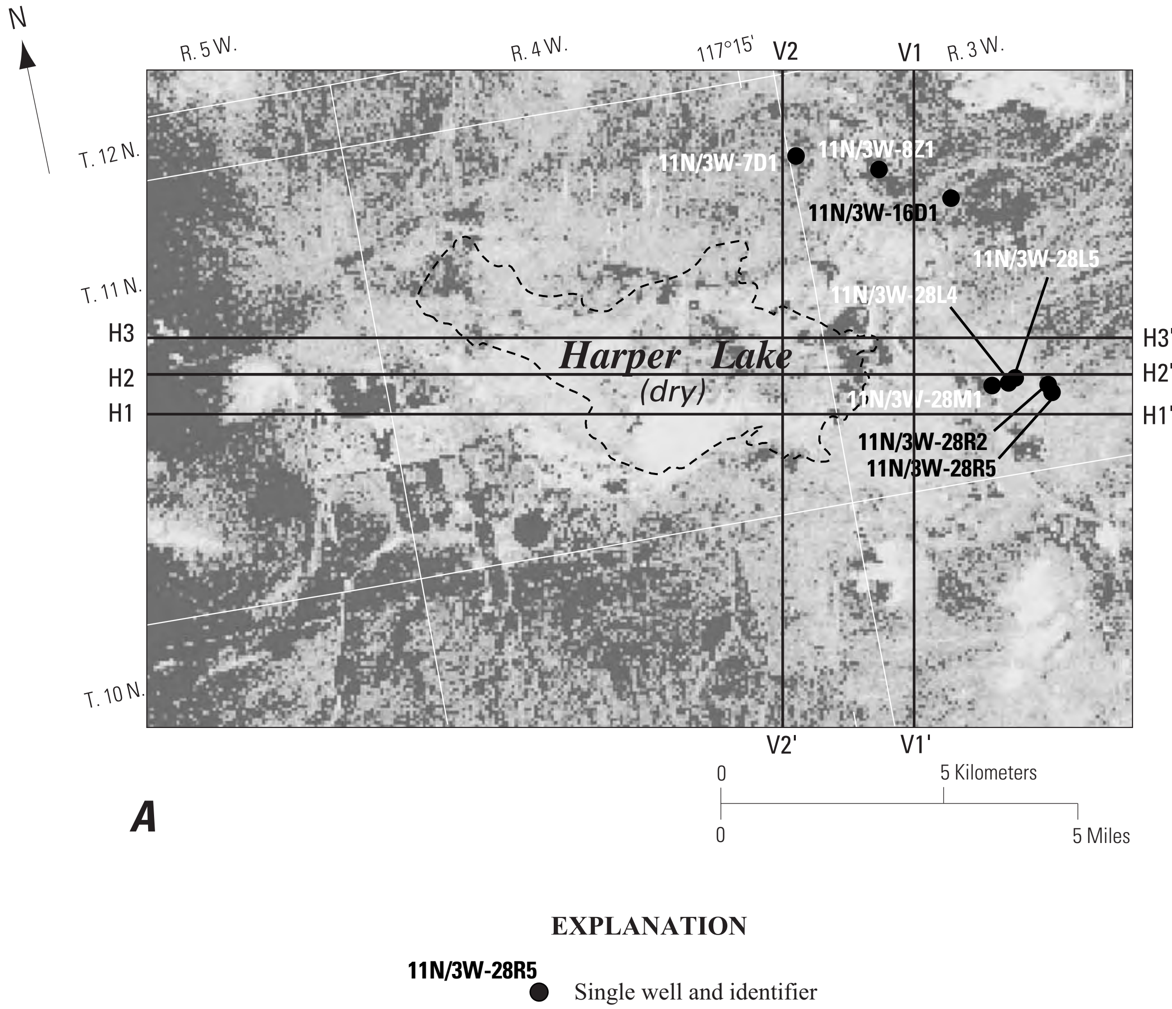
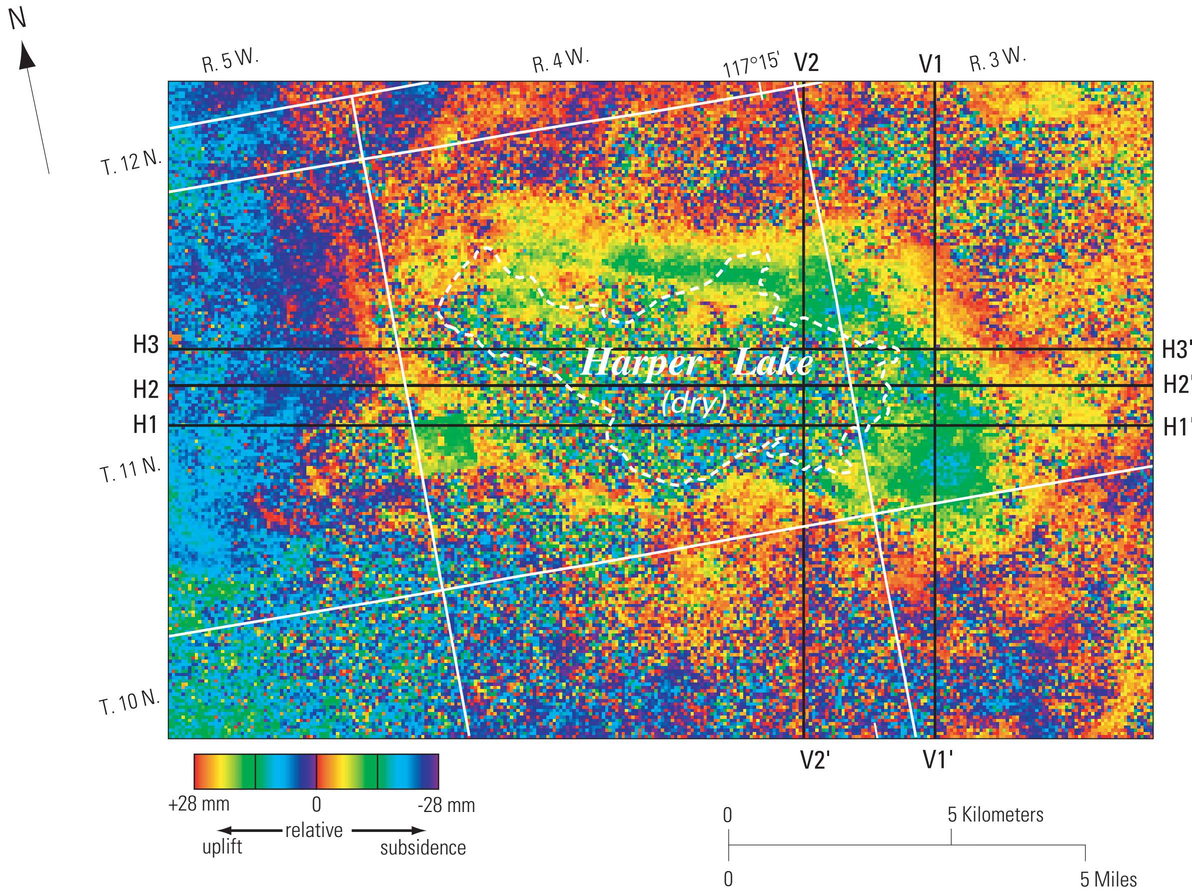


Figure 9. Amplitude image showing land-surface features and locations of wells used to evaluate subsurface geology or to monitor ground-water levels, and phase images and graphs showing vertical land-surface changes in the Lockhart—Harper Lake (dry) area, San Bernardino County, California. Amplitude image (***A***) and phase images and graphs showing land-surface change for (***B***) April 24 1992, to June 18, 1993; (***C***) June 18, 1993, to June 11, 1995; (***D***) June 11, 1995, to September 24, 1995; (***E***) September 24, 1995, to May 26, 1996, (***F***) January 8, 1996, to June 21, 1999, and (***G***) June 21, 1999, to November 8, 1999. (See figure 1 for location of area; see figure 10 for hydrographs of selected wells.)

APRIL 24, 1992–JUNE 18, 1993 (14-month interferogram)



B

Figure 9.—Continued.

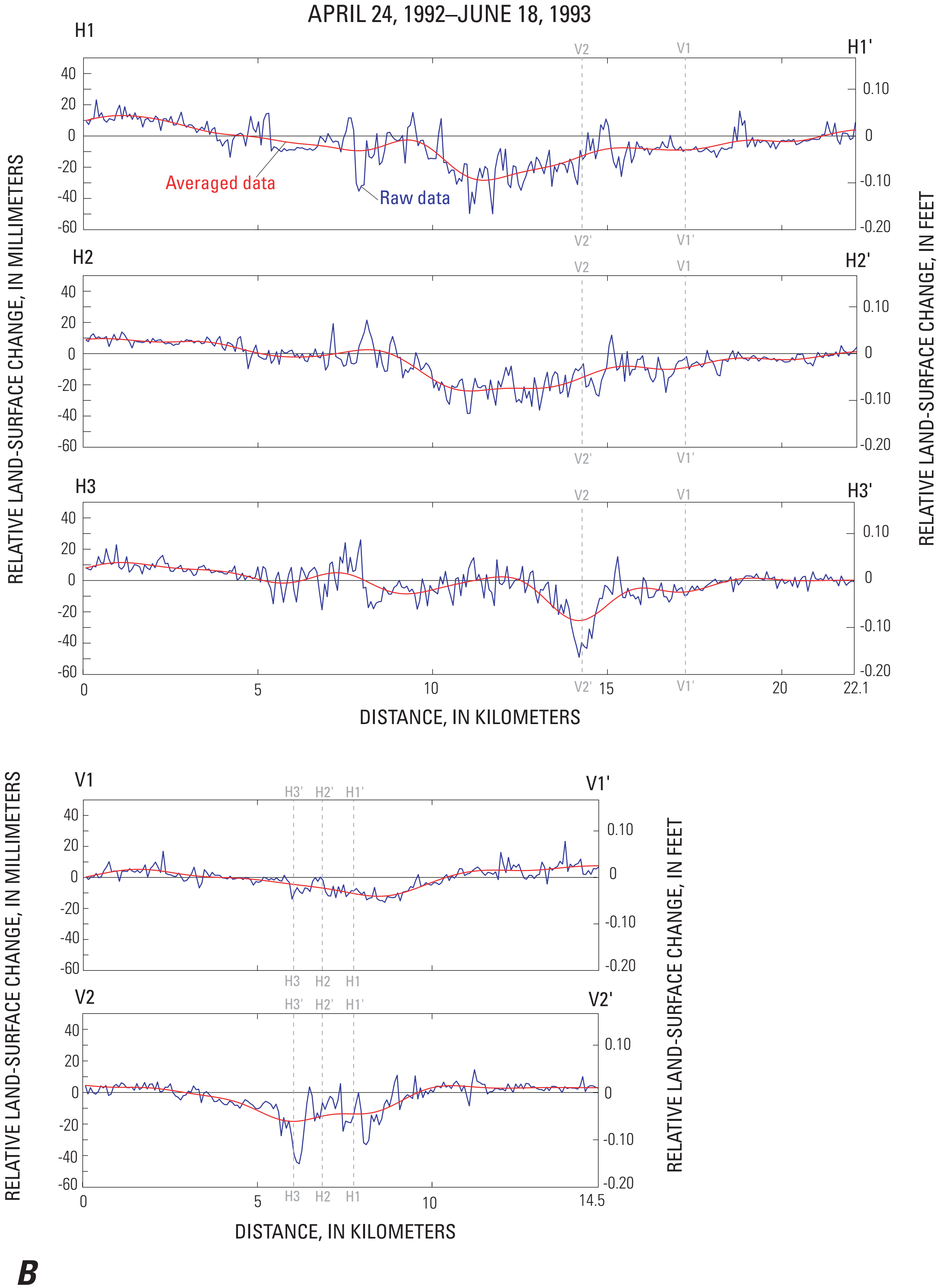
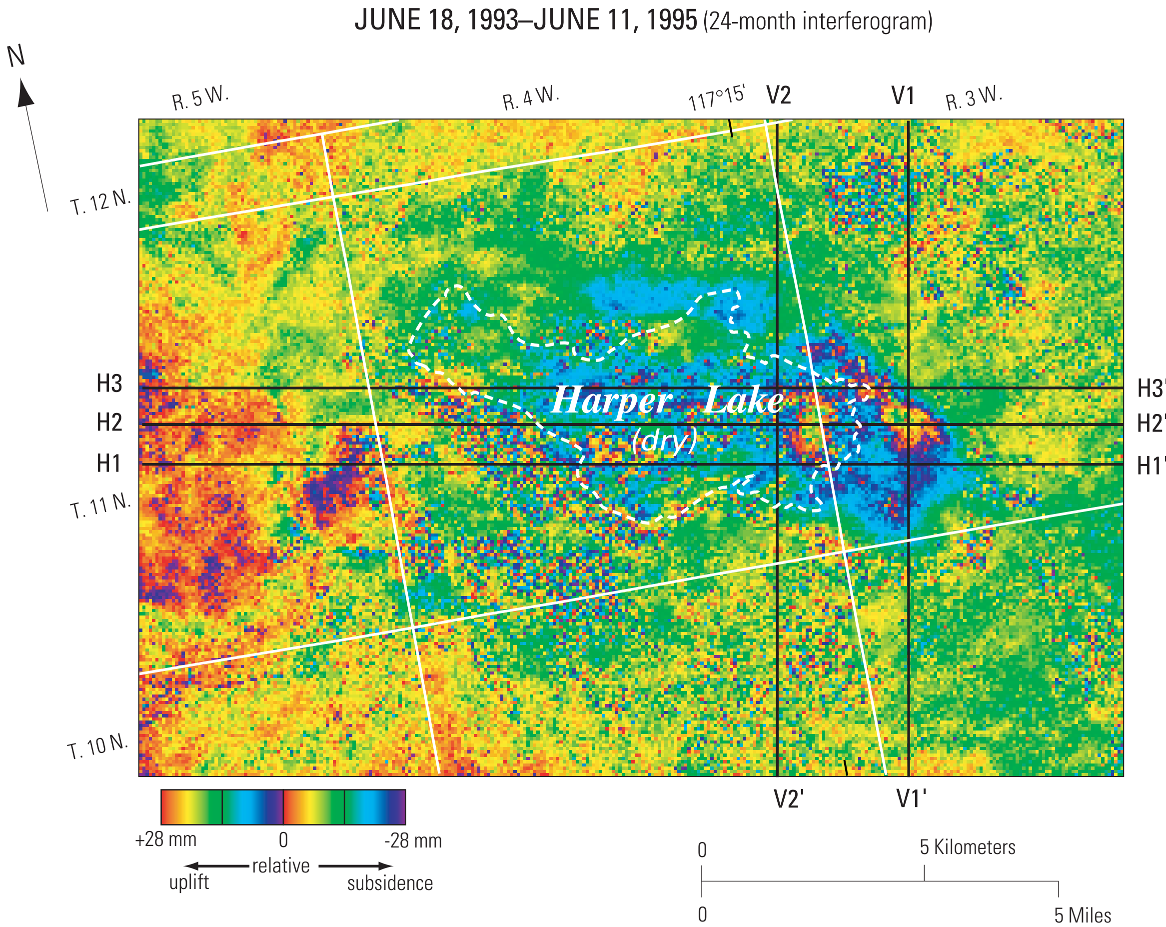


Figure 9.—Continued.



C

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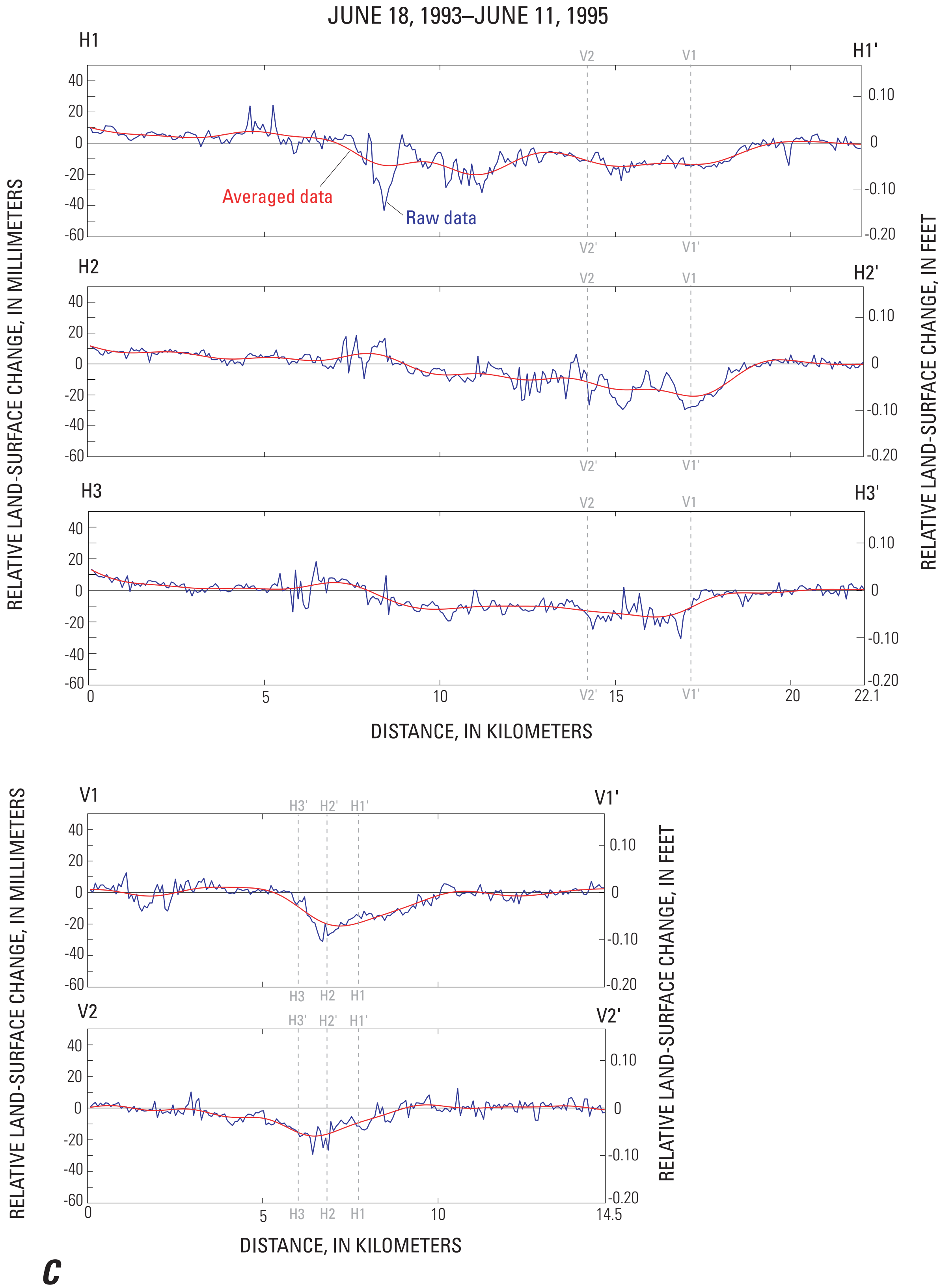

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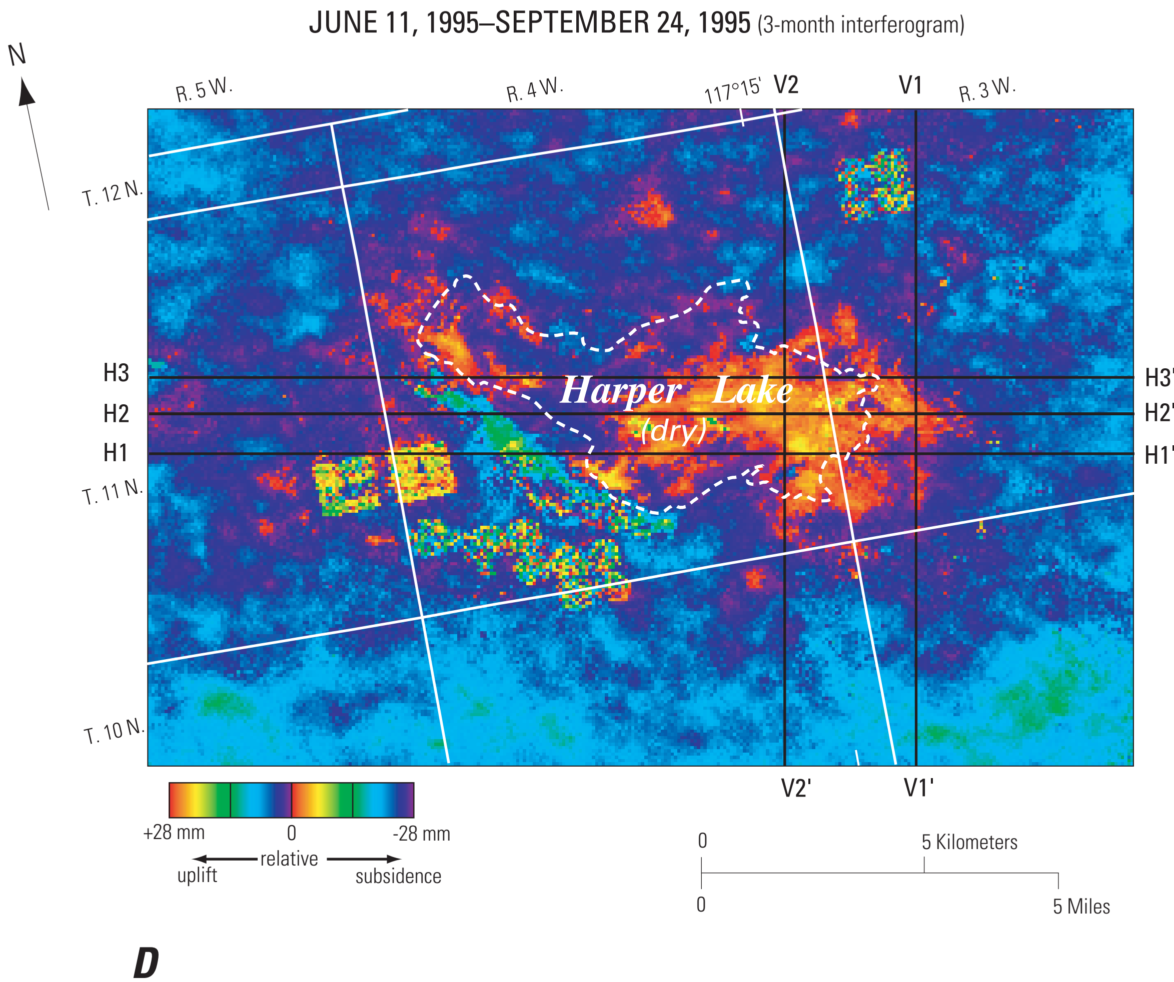

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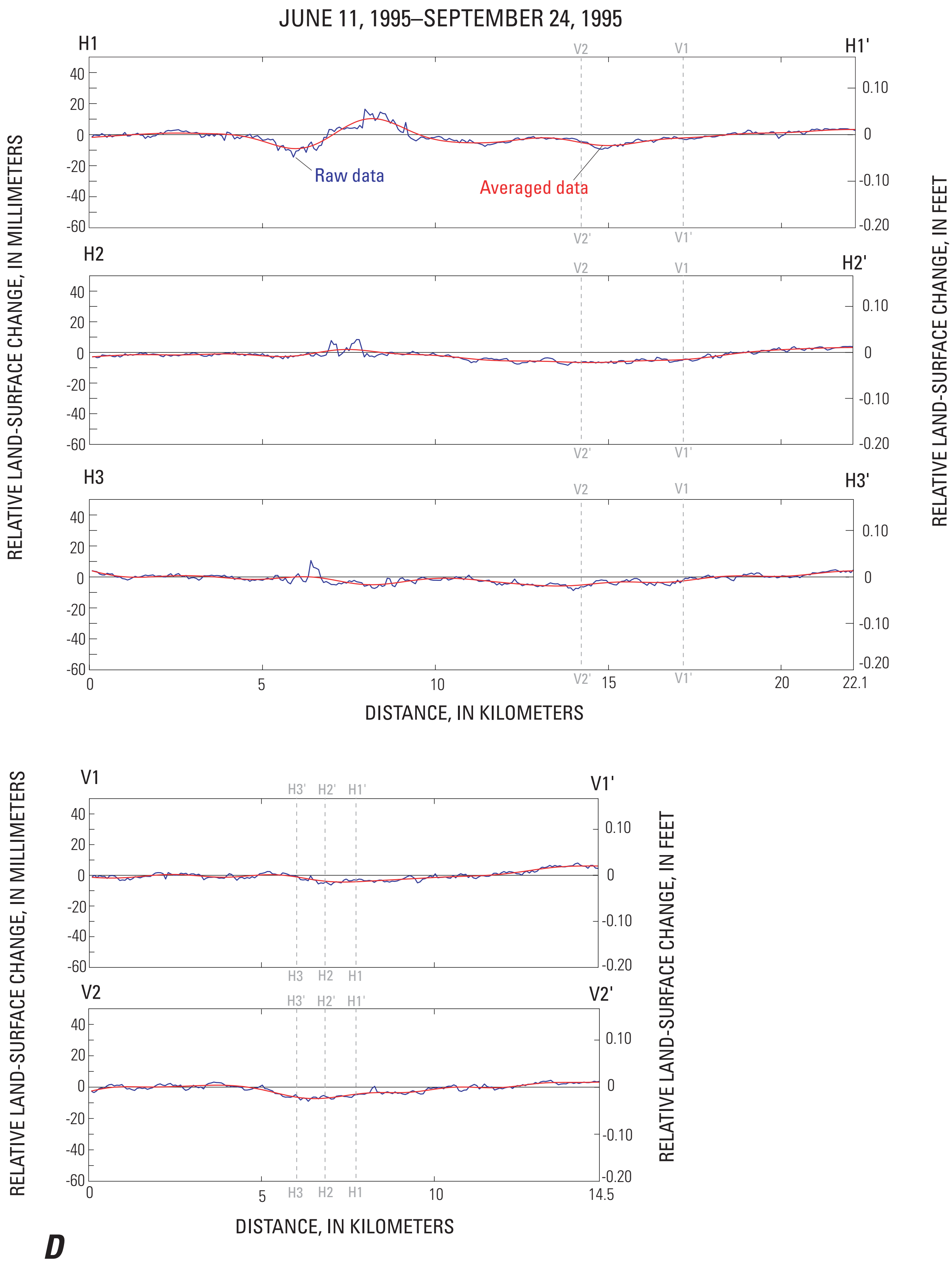

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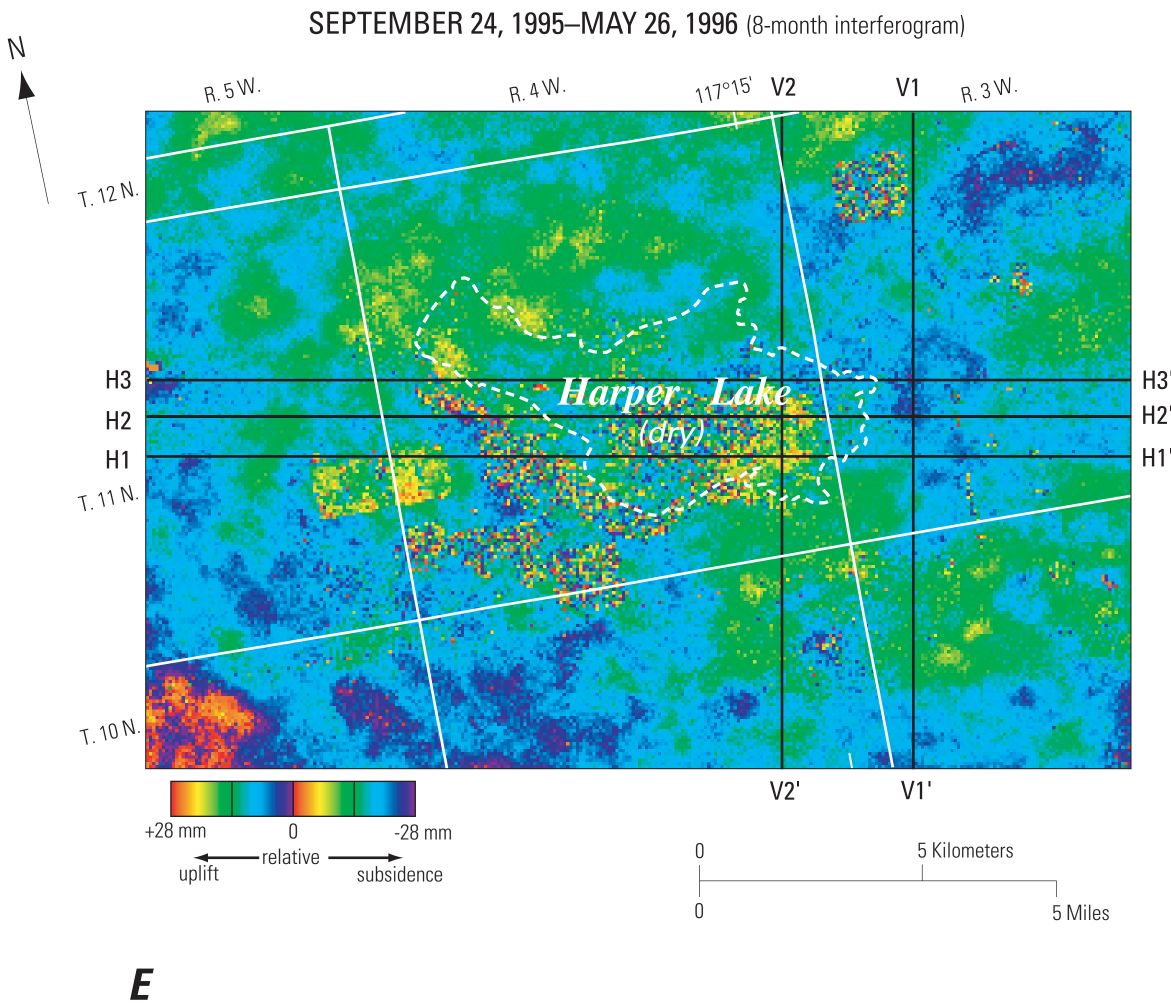

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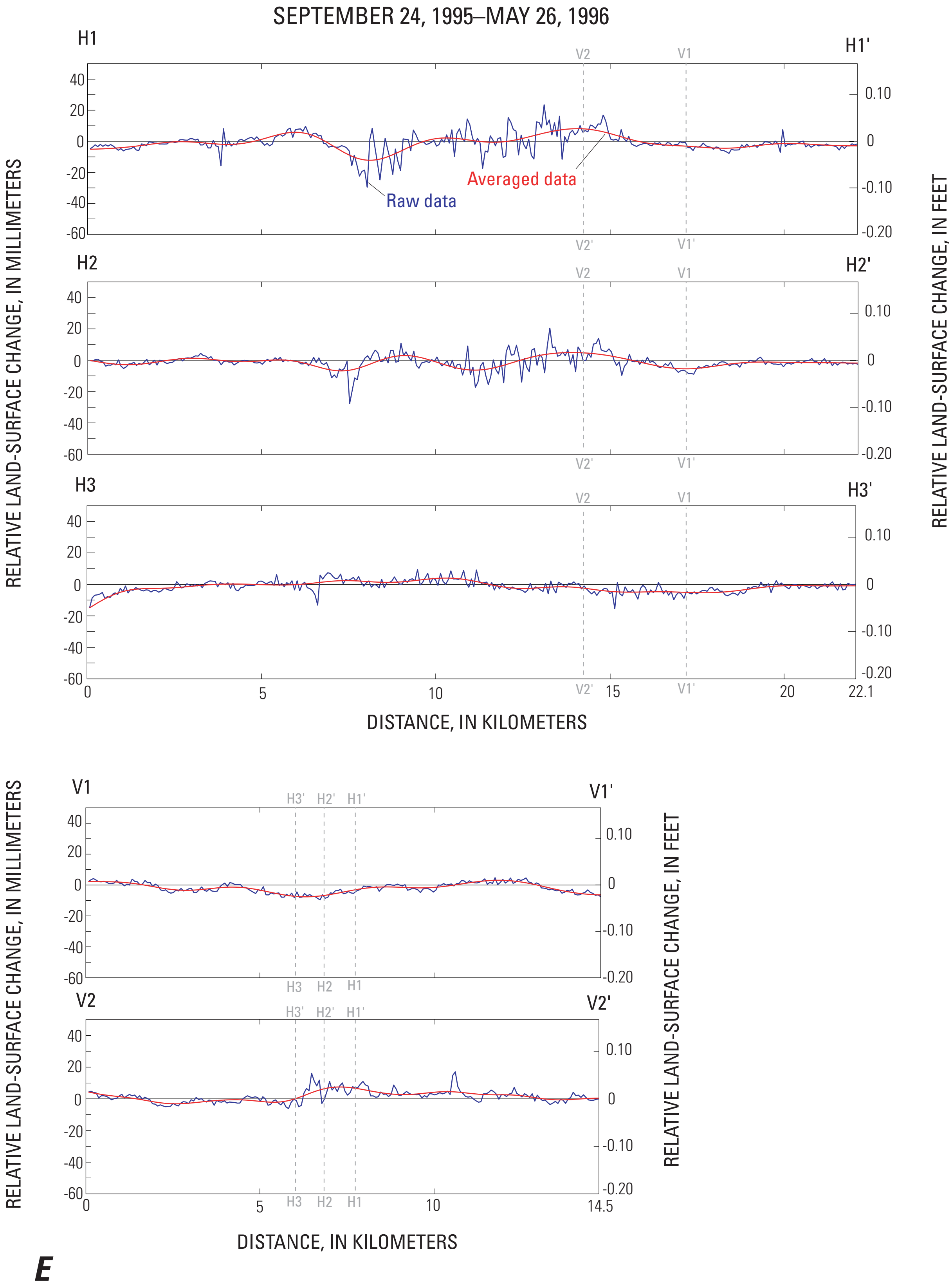
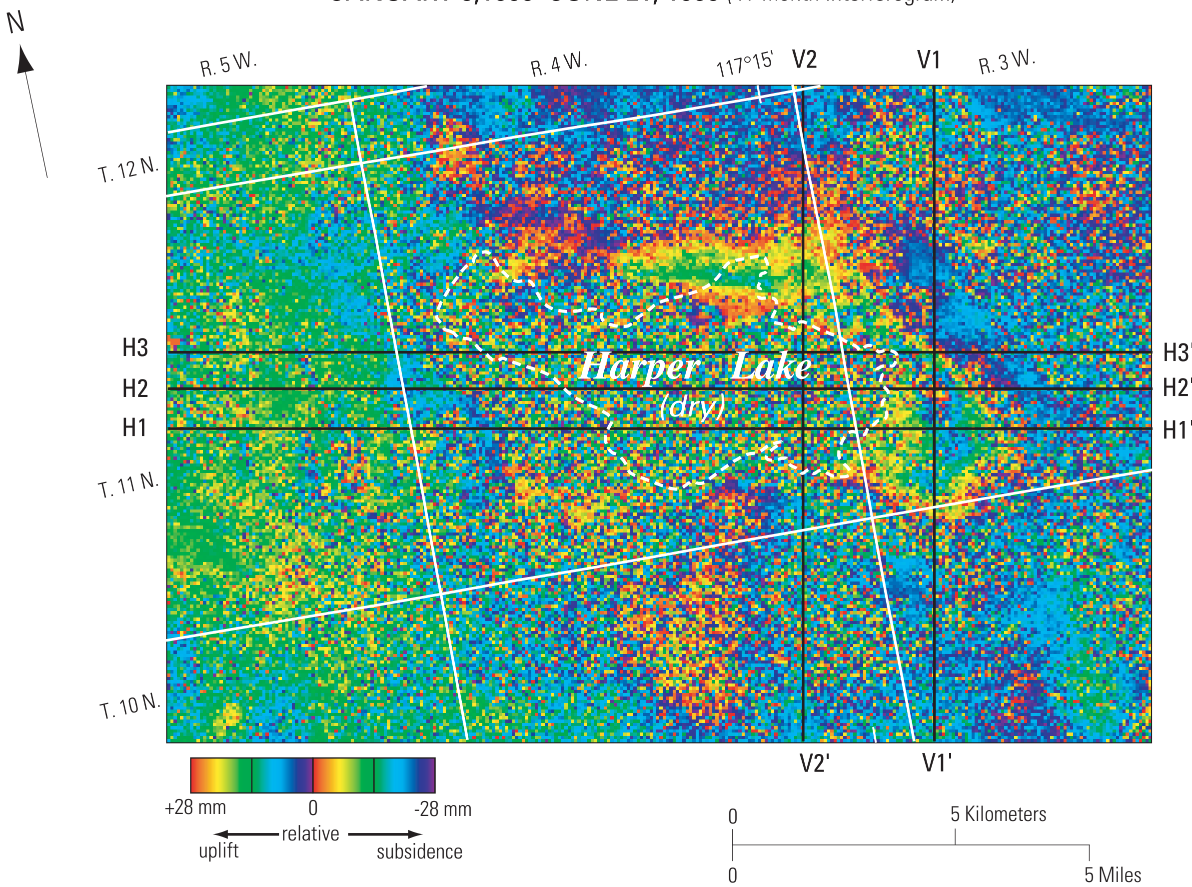


Figure 9.—Continued.

JANUARY 8,1996–JUNE 21, 1999 (41-month interferogram)



F

Figure 9.—Continued.

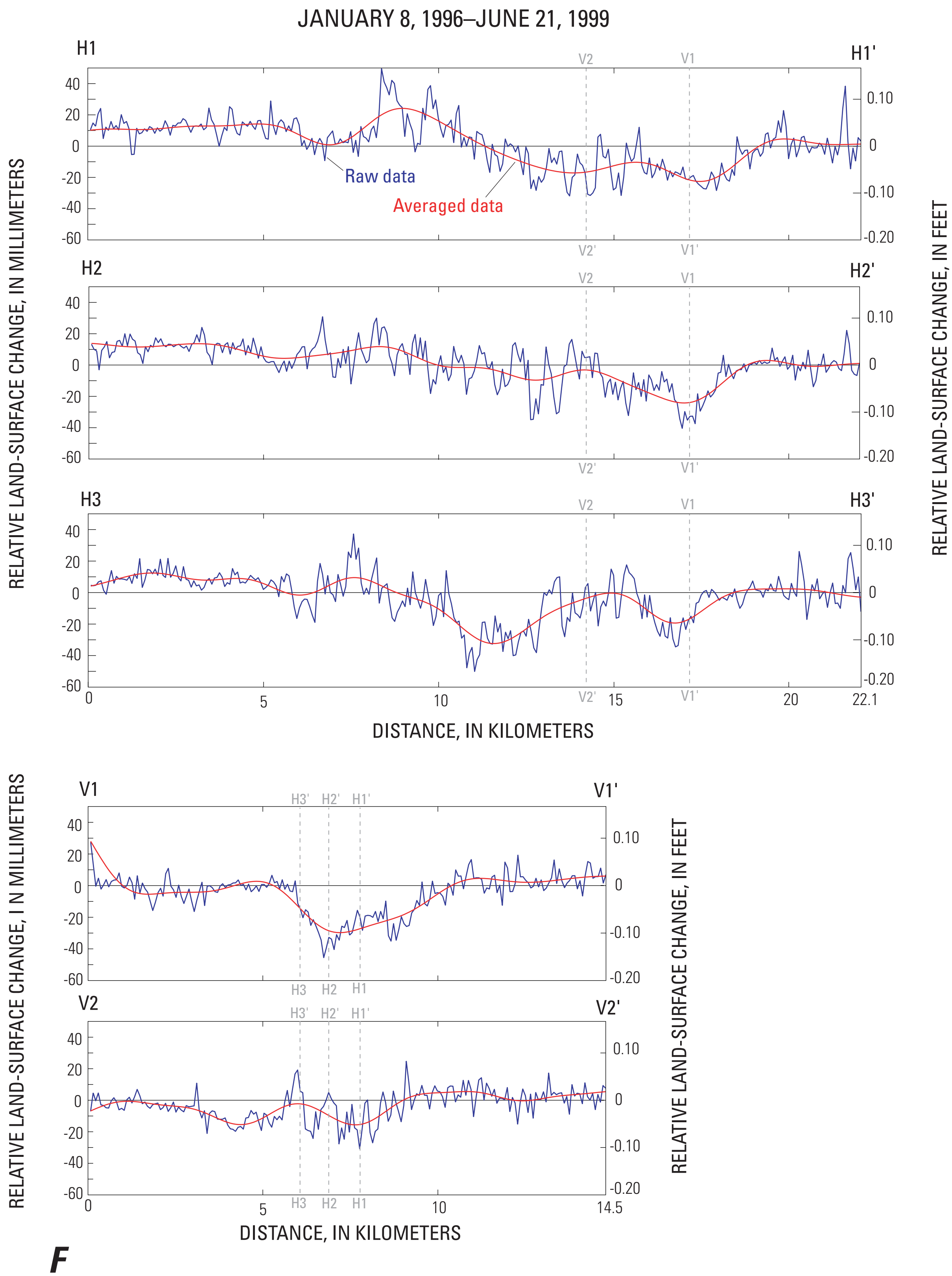
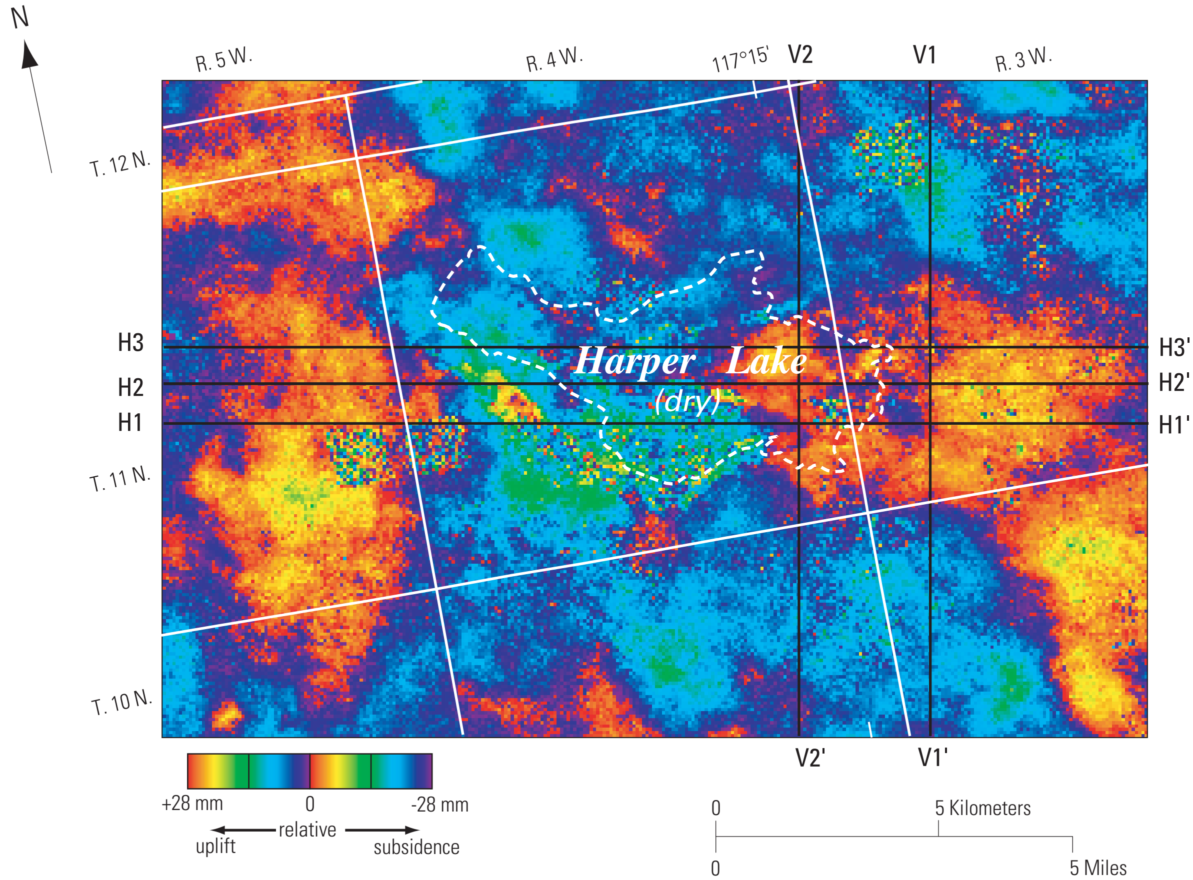


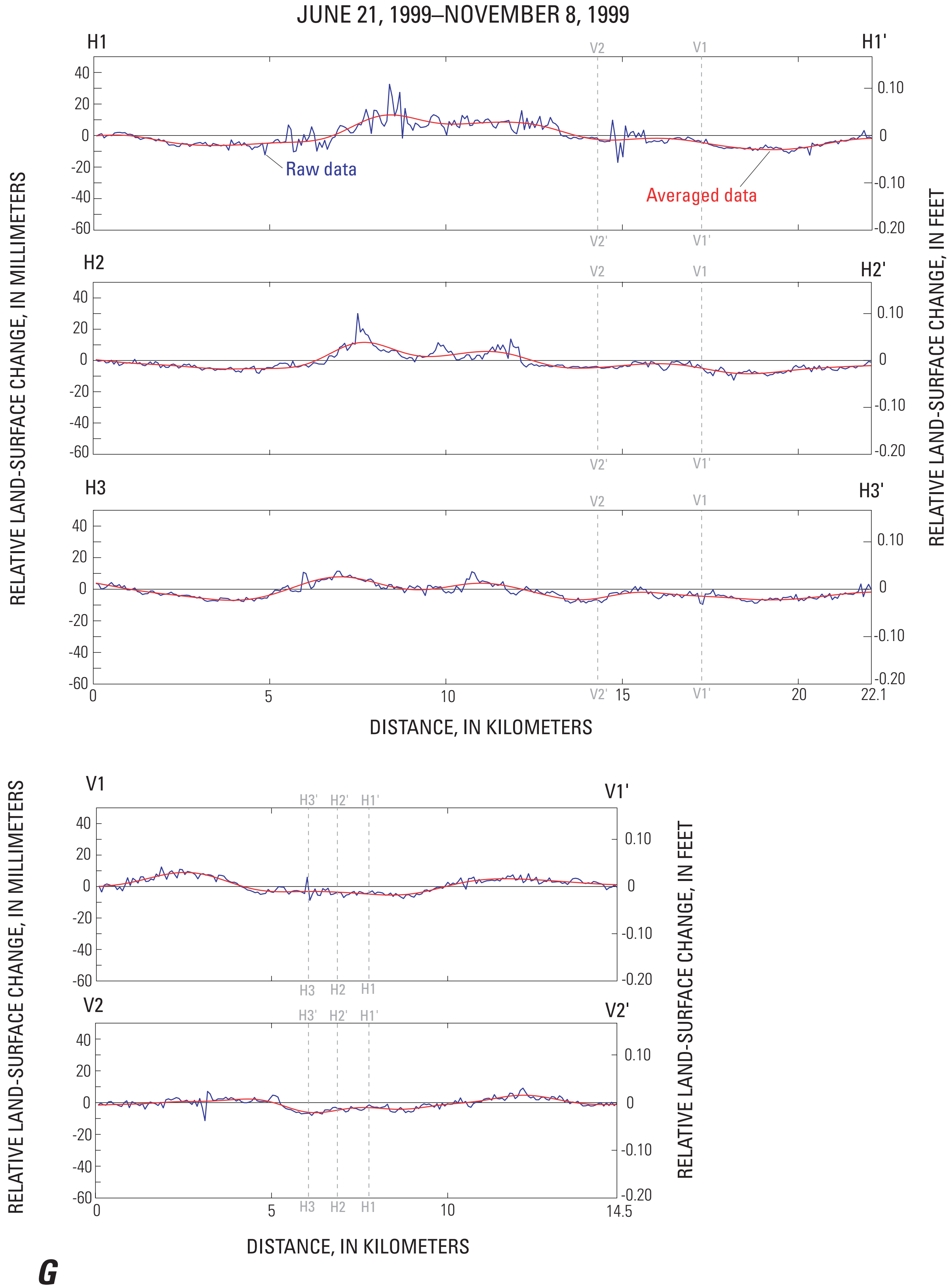
Figure 9.—Continued.

JUNE 21, 1999–NOVEMBER 8, 1999 (5-month interferogram)



G

Figure 9.—Continued.



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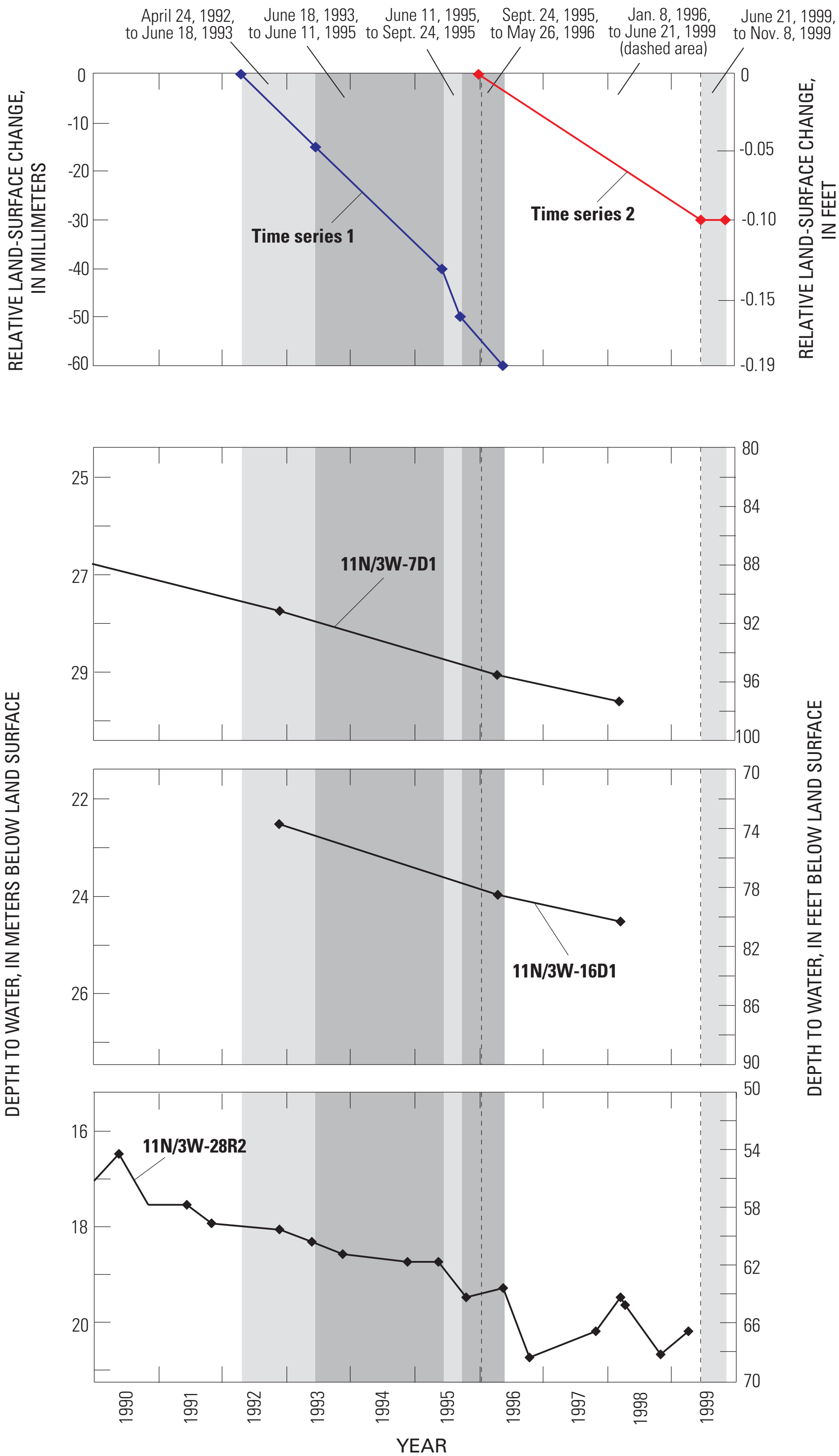


Figure 10. Depth to water for selected wells and relative land-surface change in the Lockhart–Harper Lake (dry) area, San Bernardino County, California. (See figure 9*A* for locations of wells.)

The interferograms of the Lockhart–Harper Lake (dry) area indicate that the northern and eastern shores of the playa subsided as much as 85 mm (0.28 ft) between 1992 and 1999 (fig. 10). The interferograms show a persistent pattern of deformation along the northern and eastern shores of the playa indicating as much as 60 mm (0.20 ft) of subsidence (net) between April 24, 1992, and May 26, 1996 (fig. 9*B*, *C*, *D* and *E* and time series 1 in figure 10). The 41-month interferogram [January 8, 1996, to June 21, 1999 (fig. 9*F*)] indicates that this area subsided about 30 mm (0.1 ft), and the 5-month interferogram [June 21, 1999, to November 8, 1999 (fig. 9*G*)] shows almost no change (time series 2 in figure 10).

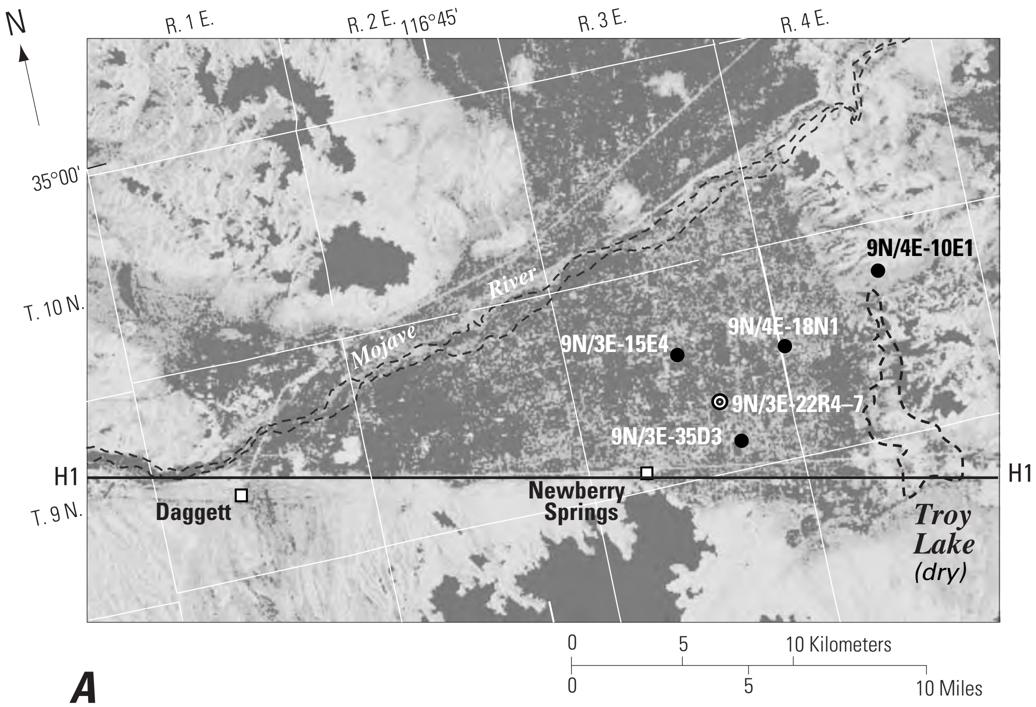
Three wells in this area have water-level records for the 1990s; the screened intervals of all three of these wells are unknown (fig. 10). Three measurements were made at wells 11N/3W-7D1 and -16D1 during the 1990s; both wells were measured in autumn 1992, spring 1996, and spring 1998. Water levels in these two wells declined about 2 m (6.5 ft) between 1992 and 1998 (fig. 10). Water-level data for well 11N/3W-7D1 indicate that water levels during the 1990s were at their lowest recorded levels (measurements were first made in 1953). Thirteen measurements were made at well 11N/3W-28R2 during 1992–99; measurements generally were made twice a year—once in the autumn and once in spring. The water-level data for this well indicate a decline of about 2.1 m (7 ft) during the 1992–99 period (fig. 10); records of water level, which date from as early as 1953, indicate that the water levels in the late 1990s were at their lowest levels. Ground-water flow simulations of the Mojave River ground-water basin show that water levels declined as much as 27 m (90 ft) between the late 1960s and 1999 (Stamos and others, 2001). The relation between concurrently declining water levels—some that were lower in the 1990s than previously recorded lows—and subsidence suggests that if declining water levels are the stresses causing the subsidence, the preconsolidation stress may have been exceeded and subsidence may be permanent in this area.

Newberry Springs Area

Six interferograms were produced for the Newberry Springs area. The interferograms comprise two temporally overlapping time-series maps of vertical land-surface deformation. The six interferograms have temporal baselines of 3, 5, 8, 14, 24, and 41 months for the period April 1992 to November 1999 (fig. 11). The 14-month [April 24, 1992, to June 18, 1993 (fig. 11*F*)], 24-month [June 18, 1993, to June 11, 1995 (fig. 11*B*)], 3-month [June 11, 1995, to September 24, 1995 (fig. 11*C*)], and 8-month [September 24, 1995, to May 26, 1996 (fig. 11*D*)], form time series 1 in figure 12; the 41-month [January 8, 1996, to June 21, 1999 (fig. 11*G*)] and 5-month [June 21, 1999, to November 8, 1999 (fig. 11*E*)] interferograms form time series 2 in figure 12.

Four of the six interferograms for the Newberry Springs area show a persistent deformation pattern about 10 km (6 mi) east of Newberry Springs near Troy Lake (dry) (fig. 11*B*, *C*, *D*, and *E*). A noticeable deformation pattern also exists about 5 km (3.1 mi) east of Newberry Springs, but it is evident only in two dependent interferograms—the 3-month [June 11, 1995, to September 24, 1995 (fig. 11*C*)] and the 8-month [September 24, 1995, to May 26, 1996 (fig. 11*D*)]—and therefore will not be discussed further. All six interferograms for the Newberry Springs area show atmospheric artifacts that may have affected the interpretations of the vertical land-surface changes. Because these atmospheric artifacts are in all the images for this area, it is likely that the tandum interferogram used to remove the topographic component of the data is the source of these artifacts. The 14-month interferogram [April 24, 1992, to June 18, 1993 (fig. 11*F*)] shows the deformation caused by the June 28, 1992, earthquake at Landers, California, and the 5-month interferogram [June 21, 1999, to November 8, 1999 (fig. 11*E*)] shows deformation caused by motion from the October 16, 1999, Hector Mine earthquake, as indicated by the many residual fringes. Many areas in the 24-month [June 18, 1993, to June 11, 1995 (fig. 11*B*)] and 41-month [January 8, 1996, to June 21, 1999 (fig. 11*G*)] interferograms have decorrelation problems owing to their fairly long temporal baselines and the agricultural land use in the area. A cross section could not be constructed for the 41-month interferogram because there was too much decorrelation.

The interferograms for the Newberry Springs area indicate that as much as 45 mm (0.15 ft) of subsidence occurred approximately 10 km (6 mi) east of Newberry Springs between 1993 and 1999 (fig. 12). Time series 1 (June 18, 1993–May 26, 1996) indicates about 5 mm (0.02 ft) of subsidence and time series 2 (September 24, 1995–November 8, 1999) indicates about 40 mm (0.13 ft) of subsidence.



EXPLANATION

9N/3E-35D3 ● **Single well and identifier**

9N/3E-22R4–7 ◎ **Cluster well and identifier**—Site at which two or more wells are installed at different depths

Figure 11. Amplitude image showing land-surface features and locations of wells and piezometers used to evaluate subsurface geology or to monitor ground-water levels, and phase images and graphs showing vertical land-surface changes in the Newberry Springs area, San Bernardino County, California. Amplitude image (***A***) and phase images and graphs showing land-surface change for (***B***) June 18, 1993, to June 11, 1995; (***C***) June 11, 1995, to September 24, 1995; (***D***) September 24, 1995, to May 26, 1996; (***E***) June 21, 1999, to November 8, 1999, (***F***) April 24, 1992, to June 18, 1993, and (***G***) January 8, 1996, to June 21, 1999. (See figure 1 for location of area; see figure 12 for hydrographs of selected wells.)

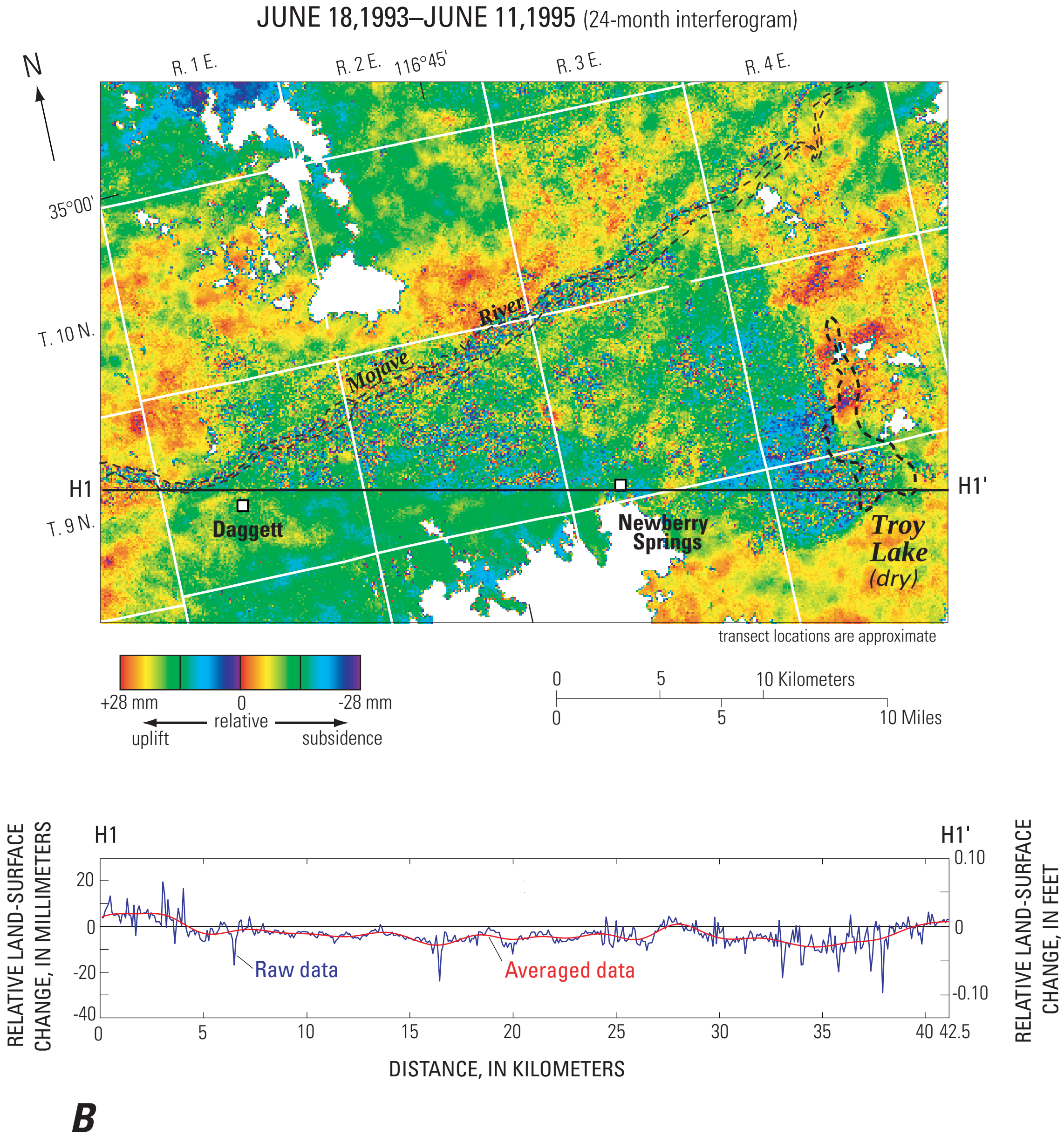


Figure 11.—Continued.

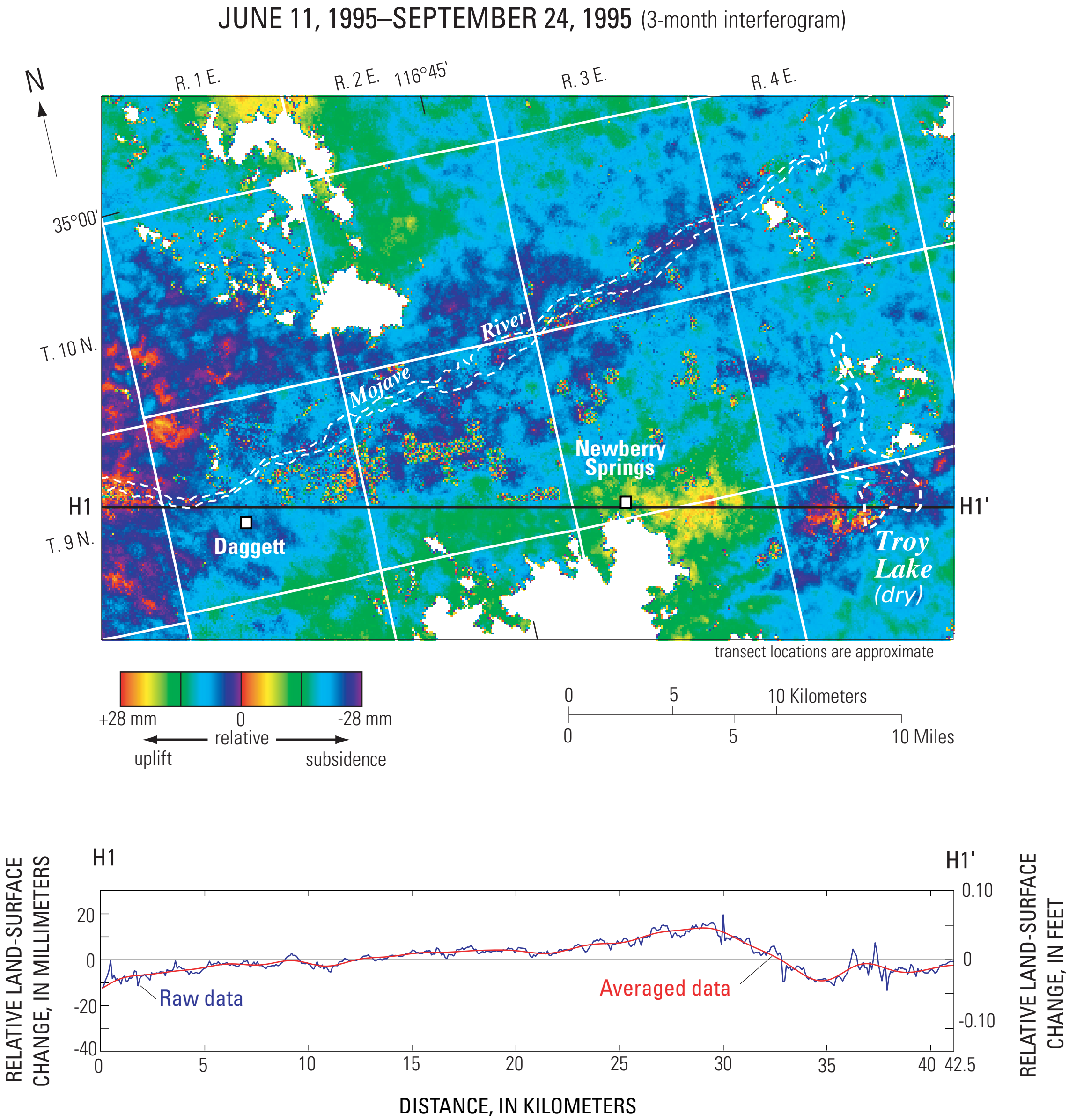


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Figure 11.—Continued.

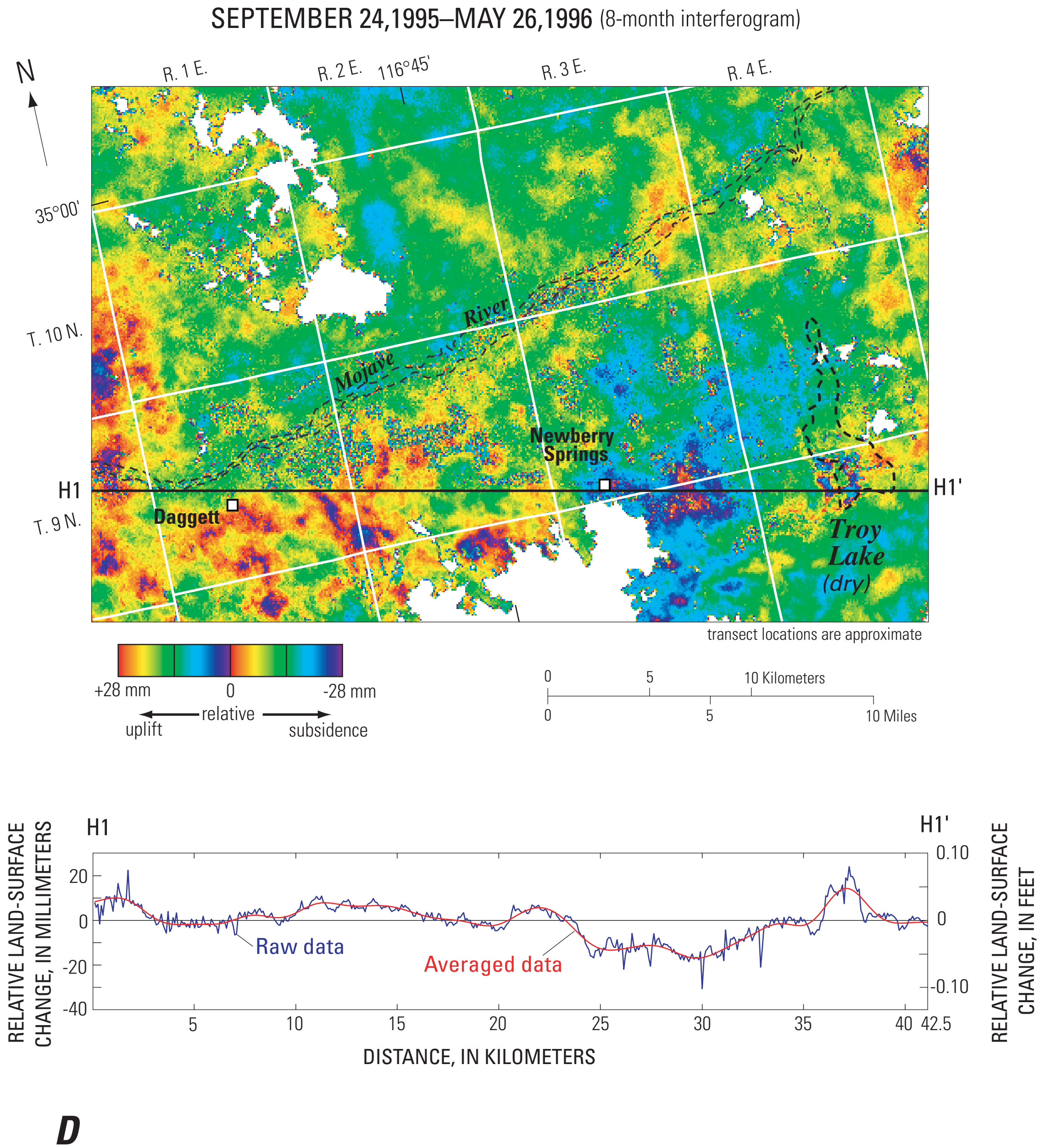


Figure 11.—Continued.

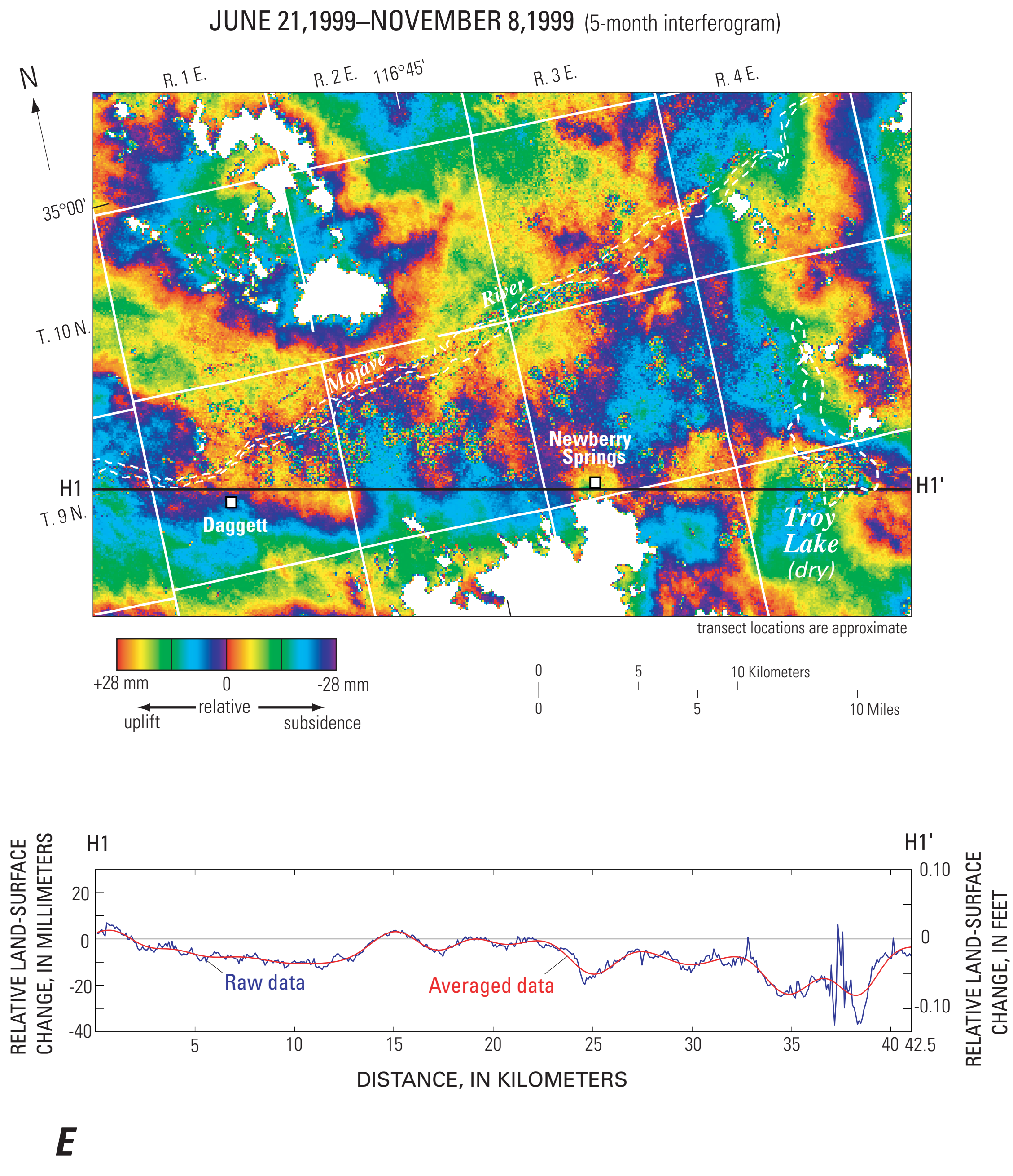
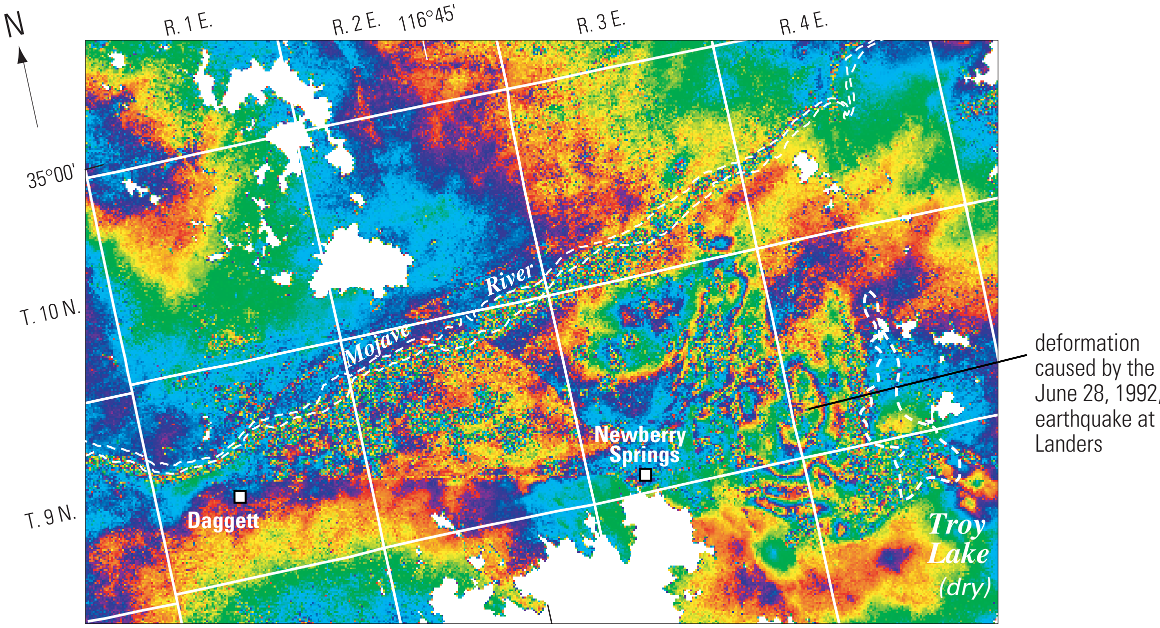


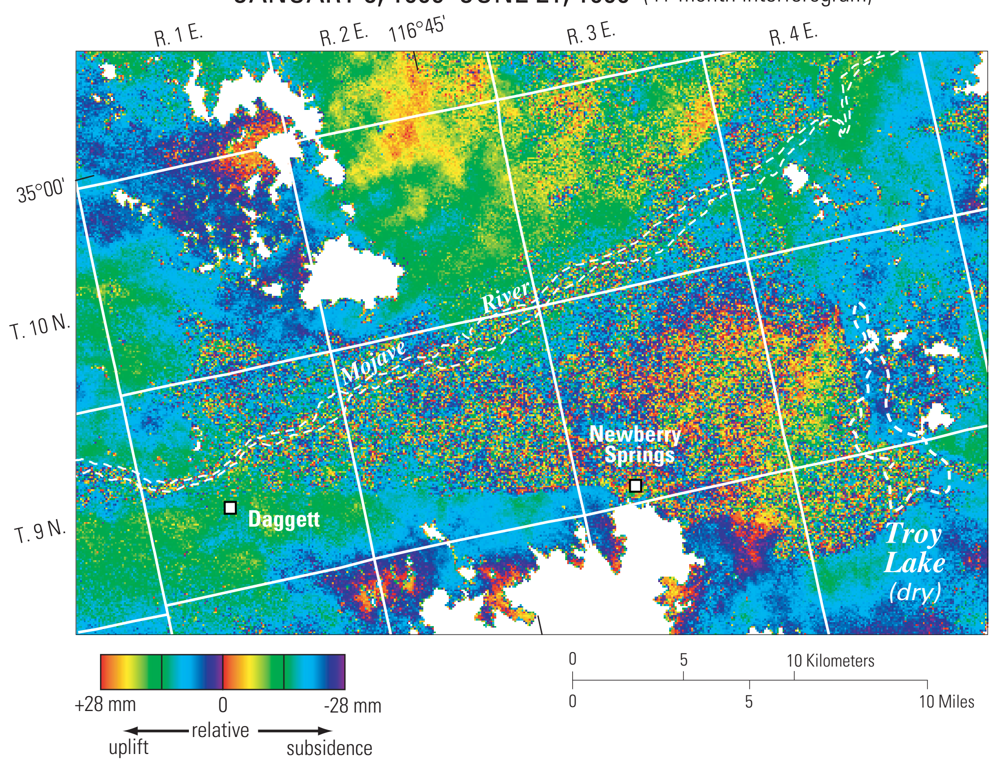
Figure 11.—Continued.

APRIL 24, 1992–JUNE 18, 1993 (14-month interferogram)



F

JANUARY 8, 1996–JUNE 21, 1999 (41-month interferogram)



G

Figure 11.—Continued.

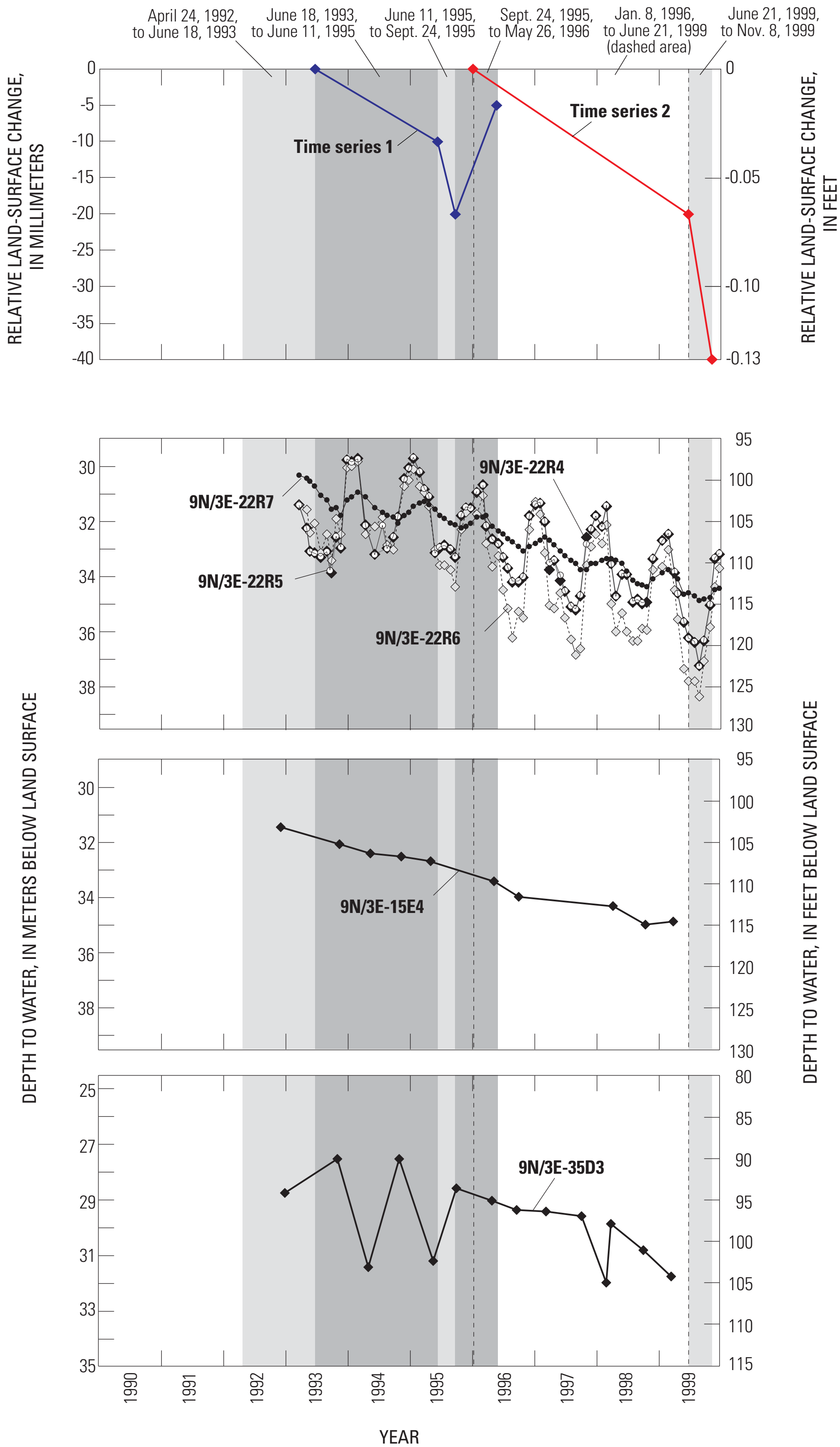


Figure 12. Depth to water for selected wells and piezometers, and relative land-surface change in the Newberry Springs area, San Bernardino County, California. (See figure 11*A* for locations of wells.)

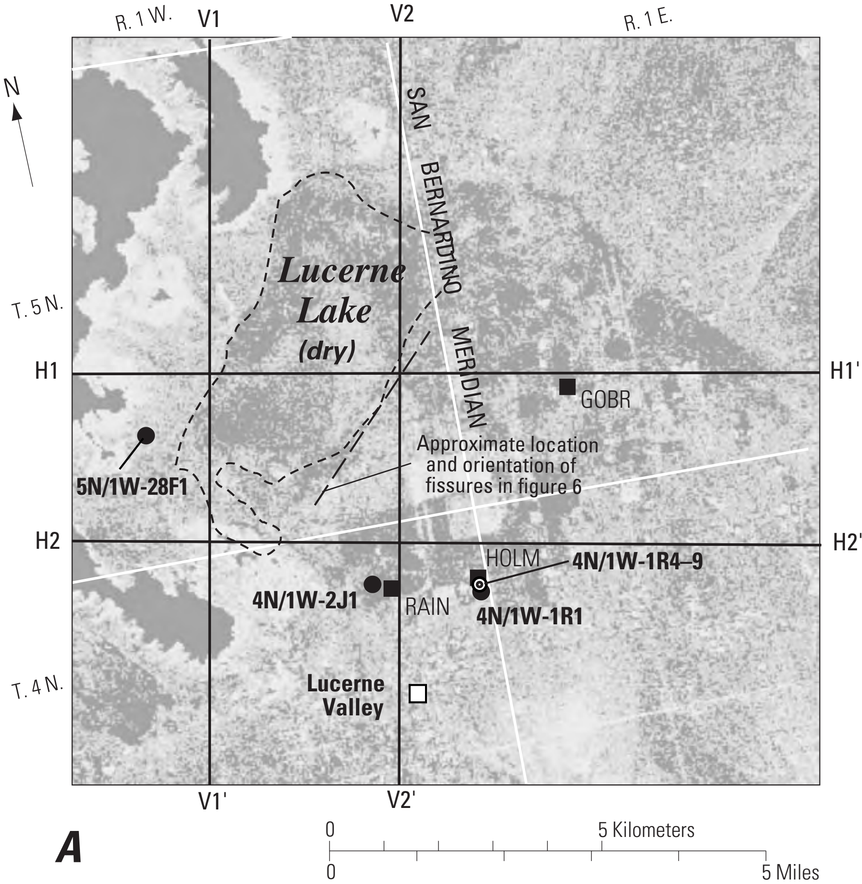
Although there are no wells in the immediate vicinity of the measured subsidence, water-level data from the closest wells were available for the 1990s (fig. 12). Water-level data for piezometers 9N/3E-22R4–7 indicate seasonal fluctuations of as much as 5.8 m (19 ft) and a long-term decline of about 3 m (10 ft) during 1993–99 (fig. 12). Piezometers 9N/3E-22R4–6 are perforated in the regional aquifer and 9N/3E-22R7 is perforated in the flood-plain aquifer; the screened intervals for these piezometers range from 30 to 183 m (100 to 600 ft) below land surface (fig. 2). Water-level data for well 9N/3E-15E4, screened in the flood-plain aquifer about 18 to 46 m (60 to 150 ft) below land surface, indicate that water levels declined about 3 m (10 ft) during 1993–99, but because water levels were measured infrequently for this well, seasonal fluctuations could not be determined (fig. 12). Water-level data for well 9N/3E-35D3, screened in the flood-plain aquifer about 18 to 67 m (60 to 219 ft) below land surface, indicate seasonal fluctuations of as much as 4 m (13 ft) during some years and longer term water-level declines of 3 m (10 ft) during 1993–99 (fig. 12). Ground-water flow simulations of the Mojave River ground-water basin show that water levels declined as much as 40 m (130 ft) in this area between the early 1940s and 1999 (Stamos and others, 2001).

Because the water levels in the six wells near Newberry Springs declined about 3 m (10 ft) between 1993 and 1999, the preconsolidation stress probably was exceeded when water levels were at their seasonal lows during each summer. Subsidence that occurred during these periods may be permanent. The geophysical and lithologic logs of piezometers 9N/3E-22R4–7 indicate that sediments more susceptible to deformation (clay and silt) are present at depths greater than 70 m (225 ft). However, lithologic logs for wells 9N/4E-10E1 and -18N1 near Troy Lake (dry) (fig. 11*A*) indicate a predominance of clay throughout the profile.

Morongo Ground-Water Basin—Lucerne Valley Area

Seven interferograms were produced for the Lucerne Valley area. The interferograms compose two temporally overlapping time-series maps of vertical land-surface deformation. The seven interferograms have temporal baselines of 3, 5, 8, 14, 24, 41 and 41 months for the period April 1992 to November 1999 (fig. 13). The 14-month [April 24, 1992, to June 18, 1993 (fig. 13*B*)], 24-month [June 18, 1993, to June 11, 1995 (fig. 13*C*)], 3-month (June 11, 1995, to September 24, 1995 (fig. 13*D*)], and 8-month [September 24, 1995, to May 26, 1996 (fig. 13*F*)] interferograms form time series 1 in figure 14. The 41-month (April 24, 1992, to September 24, 1995 (fig. 13*E*)] interferogram temporally envelopes much of this time series. The 41-month [January 8, 1996, to June 21, 1999 (fig. 13*G*)] and 5-month [June 21, 1999, to November 8, 1999 (fig. 13H)] interferograms form time series 2 in figure 14.

The seven interferograms for Lucerne Valley (fig. 13) show two deformation patterns: one just southeast of the southeastern shore of the playa near the intersection of cross-section lines H2–H2′ and V2–V2′ and one along the western shore of Lucerne Lake (dry) near the intersection of cross-section lines H1–H1′ and V1–V1′ (fig. 13). The location of the former pattern coincides with the location of an area that subsided about 600 mm (2 ft) ±1,500 mm (5 ft) (determined from topographic maps and GPS measurements for the 1969–98 or the 1975–98 period). All seven interferograms for Lucerne Valley (fig. 13) have decorrelation problems, as evidenced by the speckled patterns appearing in the interferograms, because much of the land surface has been disturbed owing to agricultural practices. The decorrelation also can be attributed to wet periods during which flooding and (or) deposition occurred on the playa, movement along faults, or strong winds. Additionally, the 14-month [April 24, 1992, to June 18, 1993 (fig. 13*B*)] and the 41-month [April 24, 1992, to September 24, 1995 (fig. 13*E*)] interferograms show deformation caused by motion from the June 28, 1992, earthquake at Landers. Deformation caused by the motion from the October 16, 1999, Hector Mine earthquake is evident in the 5-month [June 21, 1999, to November 8, 1999 (fig. 13*H*)] interferogram.



EXPLANATION

Single well and identifier

Cluster well and identifier—Site at which two or more wells are installed at different depths

Global Positioning System (GPS) station and identifier

Figure 13. Amplitude image showing land-surface features and locations of wells and piezometers used to evaluate subsurface geology or to monitor ground-water levels, and phase images and graphs showing vertical land-surface changes in the Lucerne Valley area, San Bernardino County, California. Amplitude image (***A***) and phase images and graphs showing land-surface change for (***B***) April 24, 1992, to June 18, 1993; (***C***) June 18, 1993, to June 11, 1995; (***D***) June 11, 1995, to September 24, 1995; (***E***) April 24, 1992, to September 24, 1995, (***F***) September 24, 1995, to May 26, 1996, and (***G***) January 8, 1996, to June 21, 1999, and (***H***) June 21, 1999, to November 8, 1999. (See figure 1 for location of area; see figure 14 for hydrographs of selected wells.)

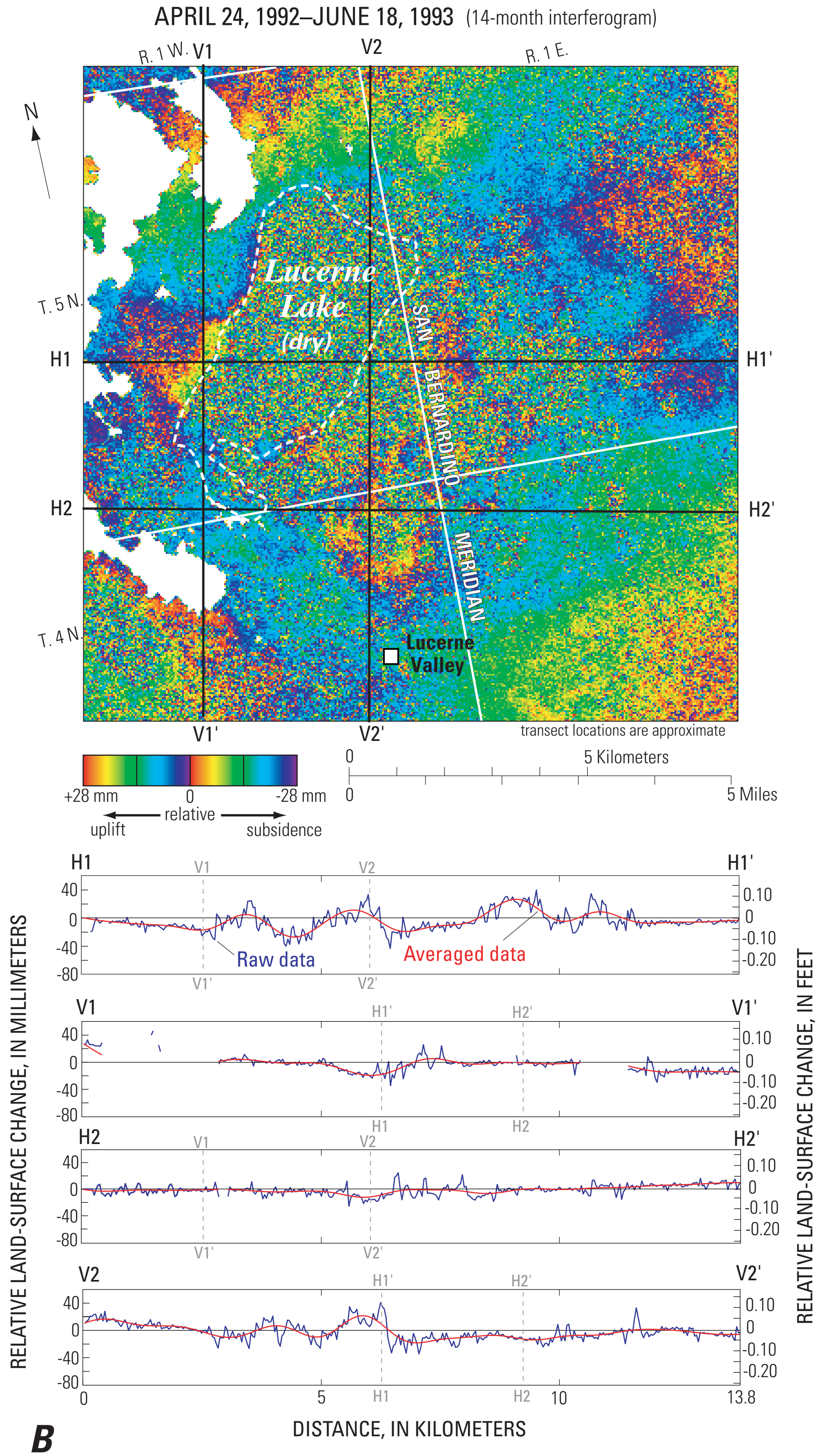
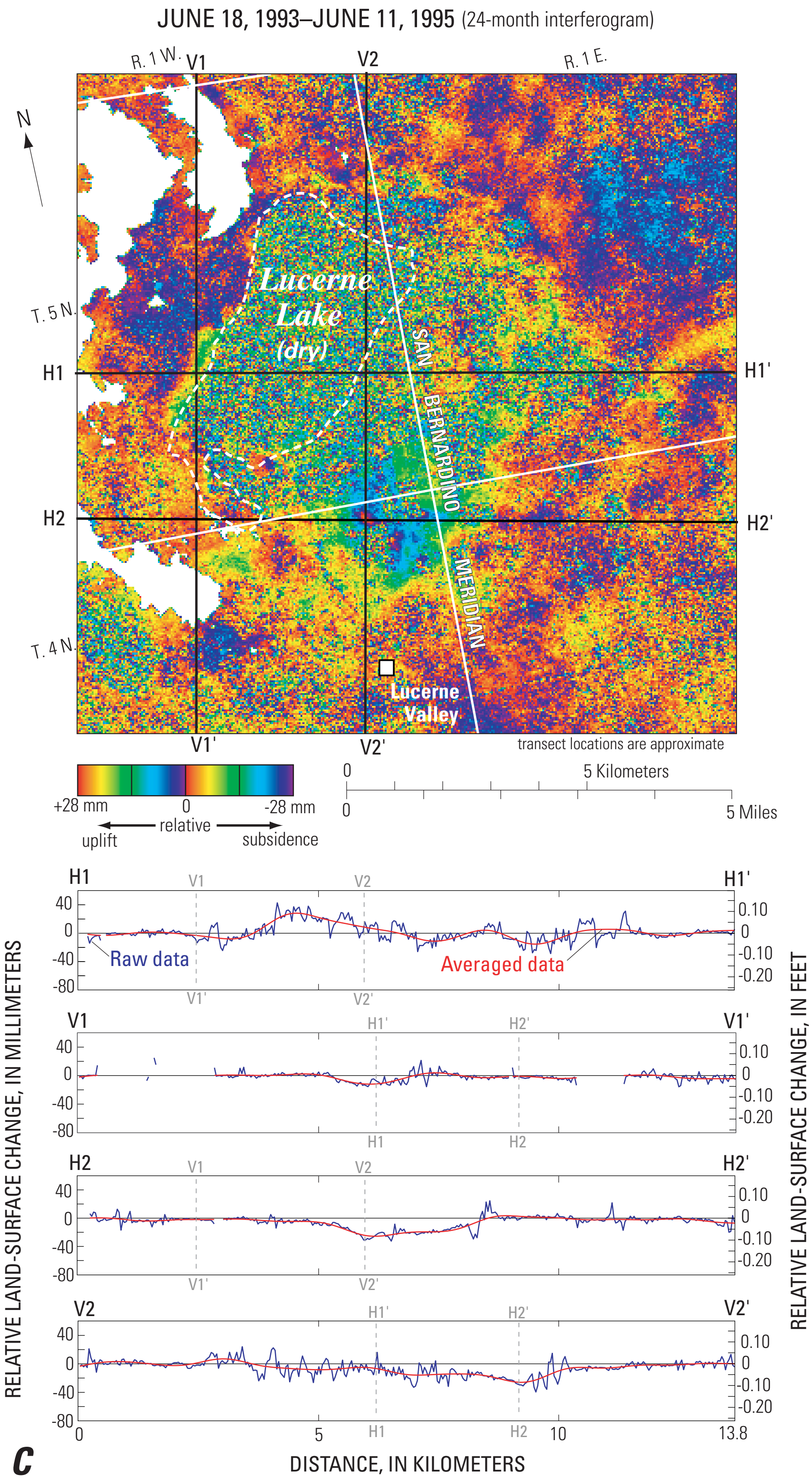


Figure 13.—Continued.



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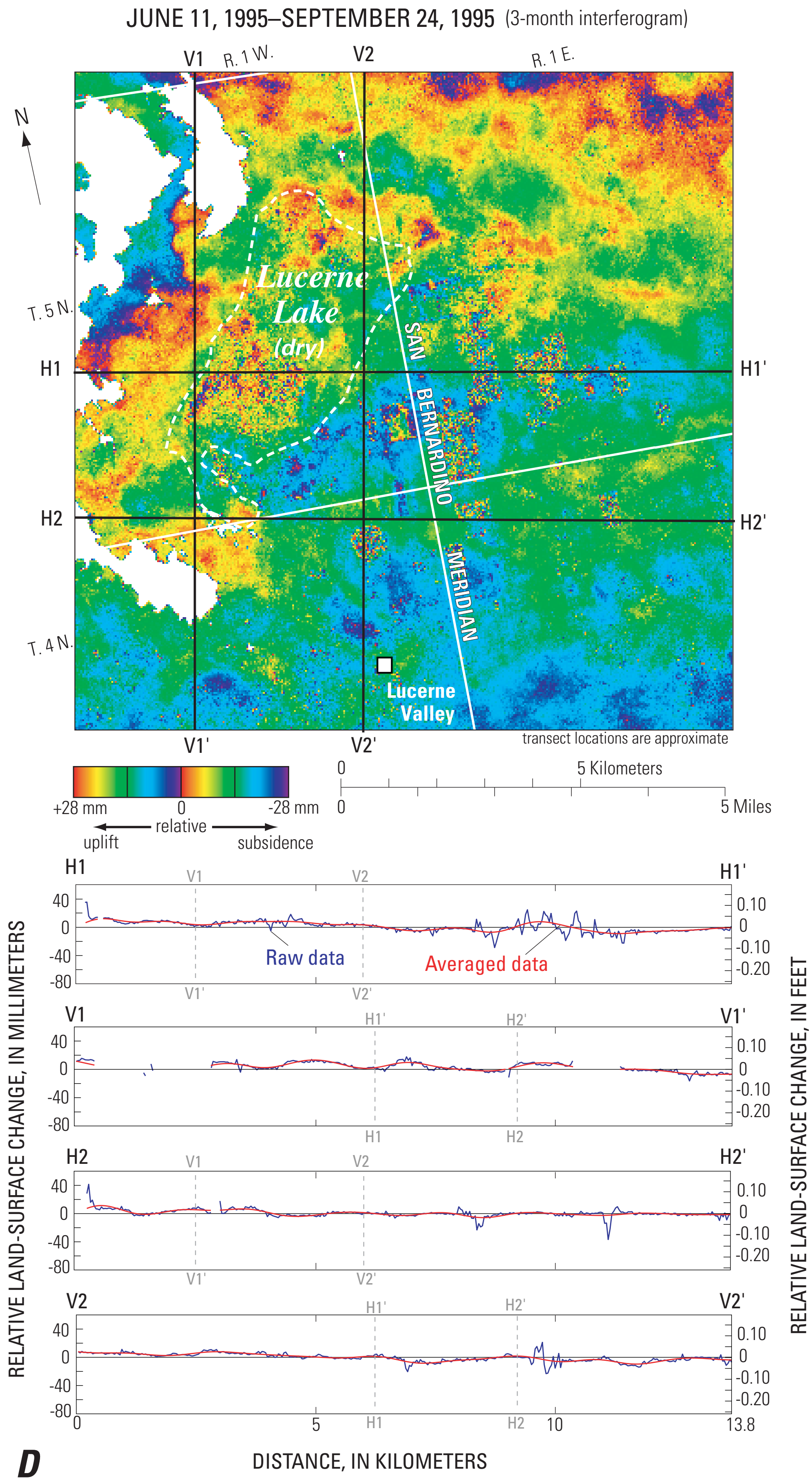

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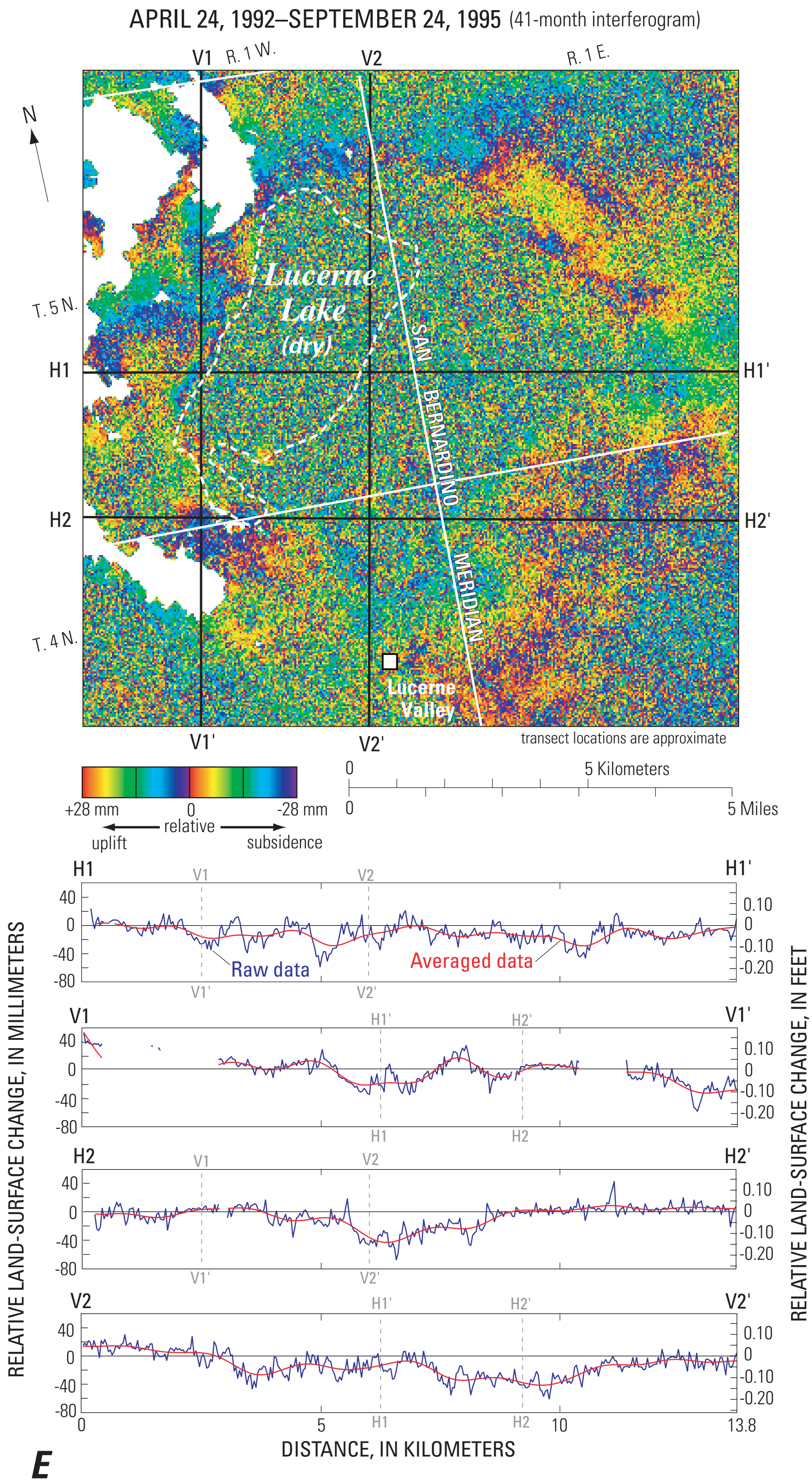

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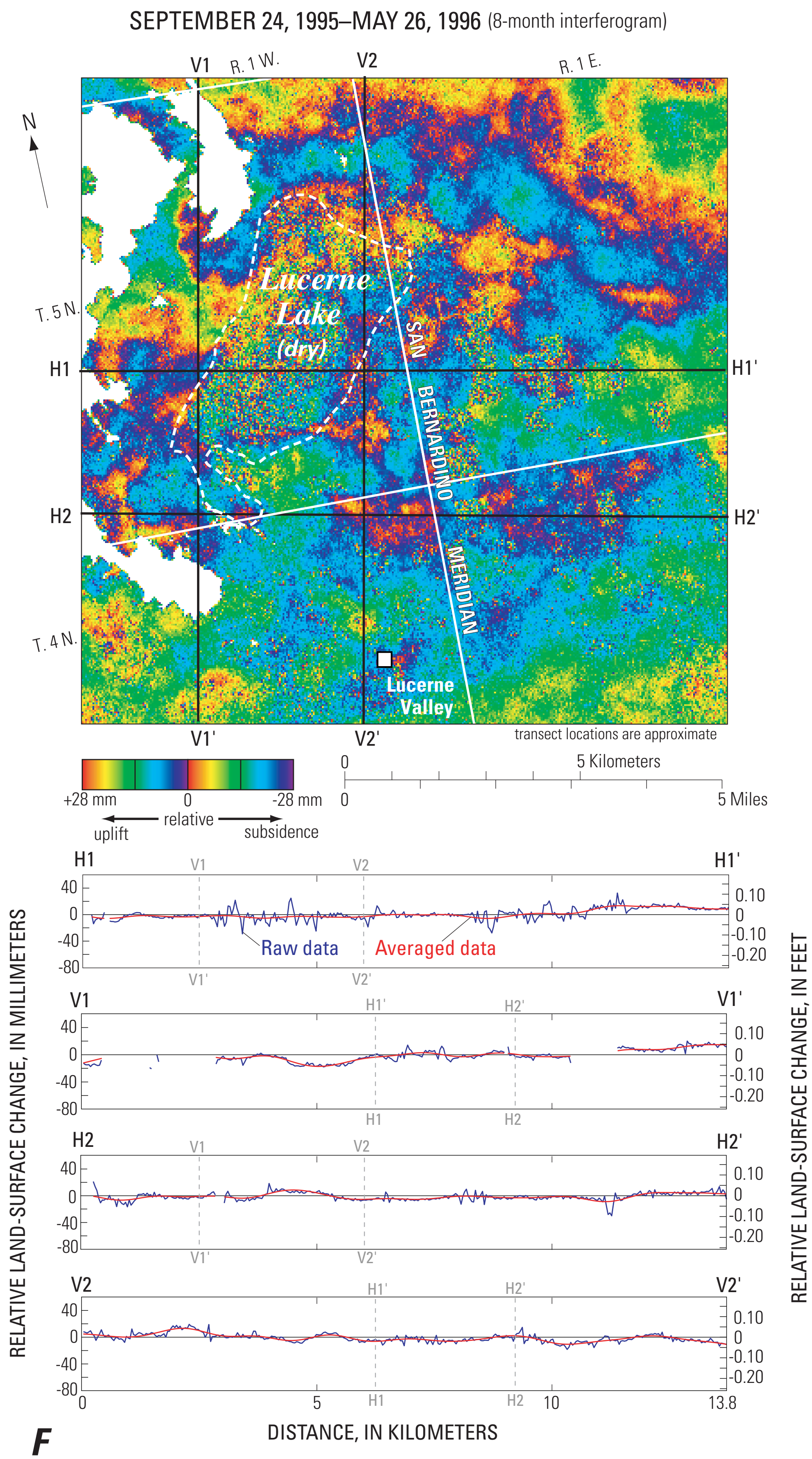

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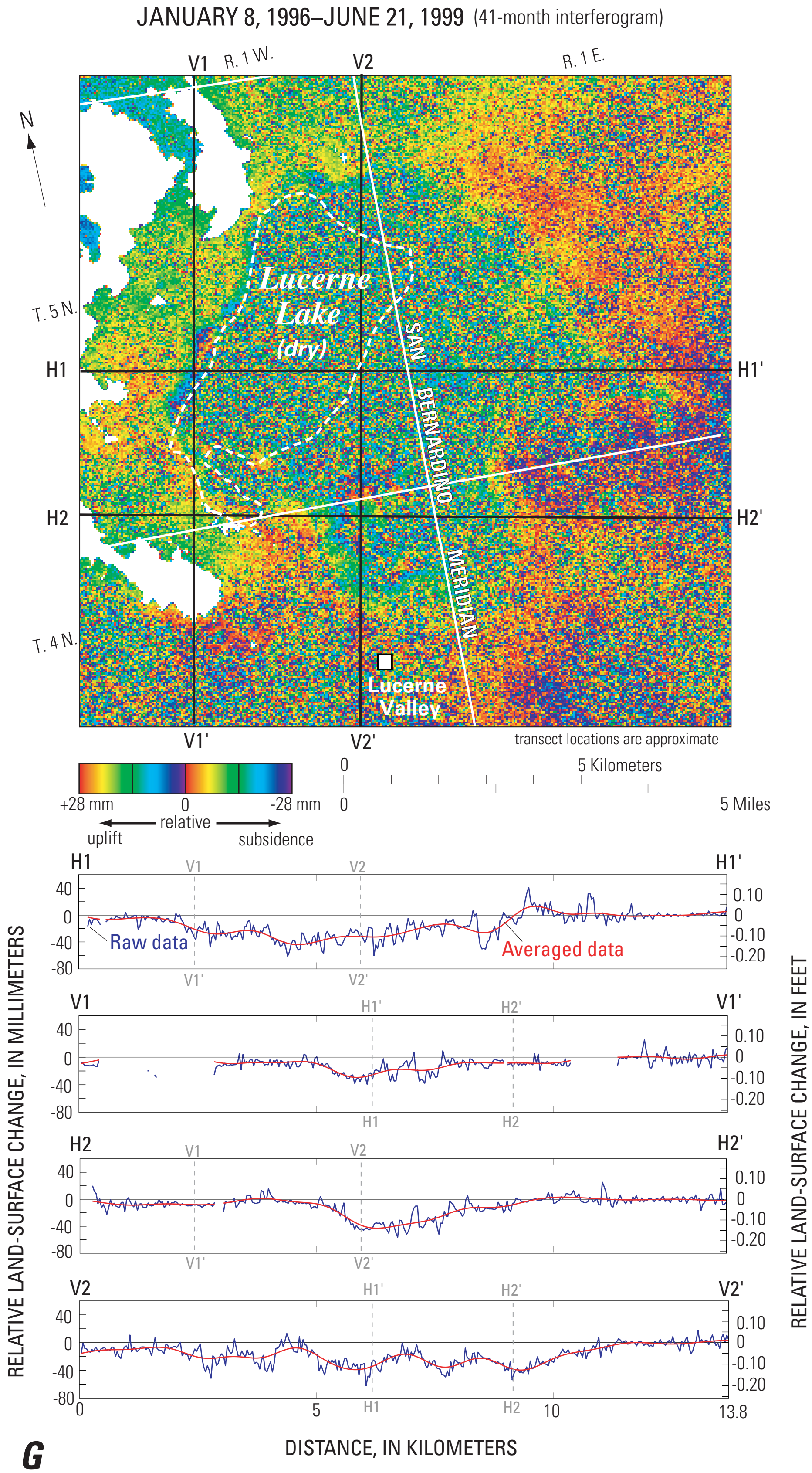

Figure 13.—Continued.

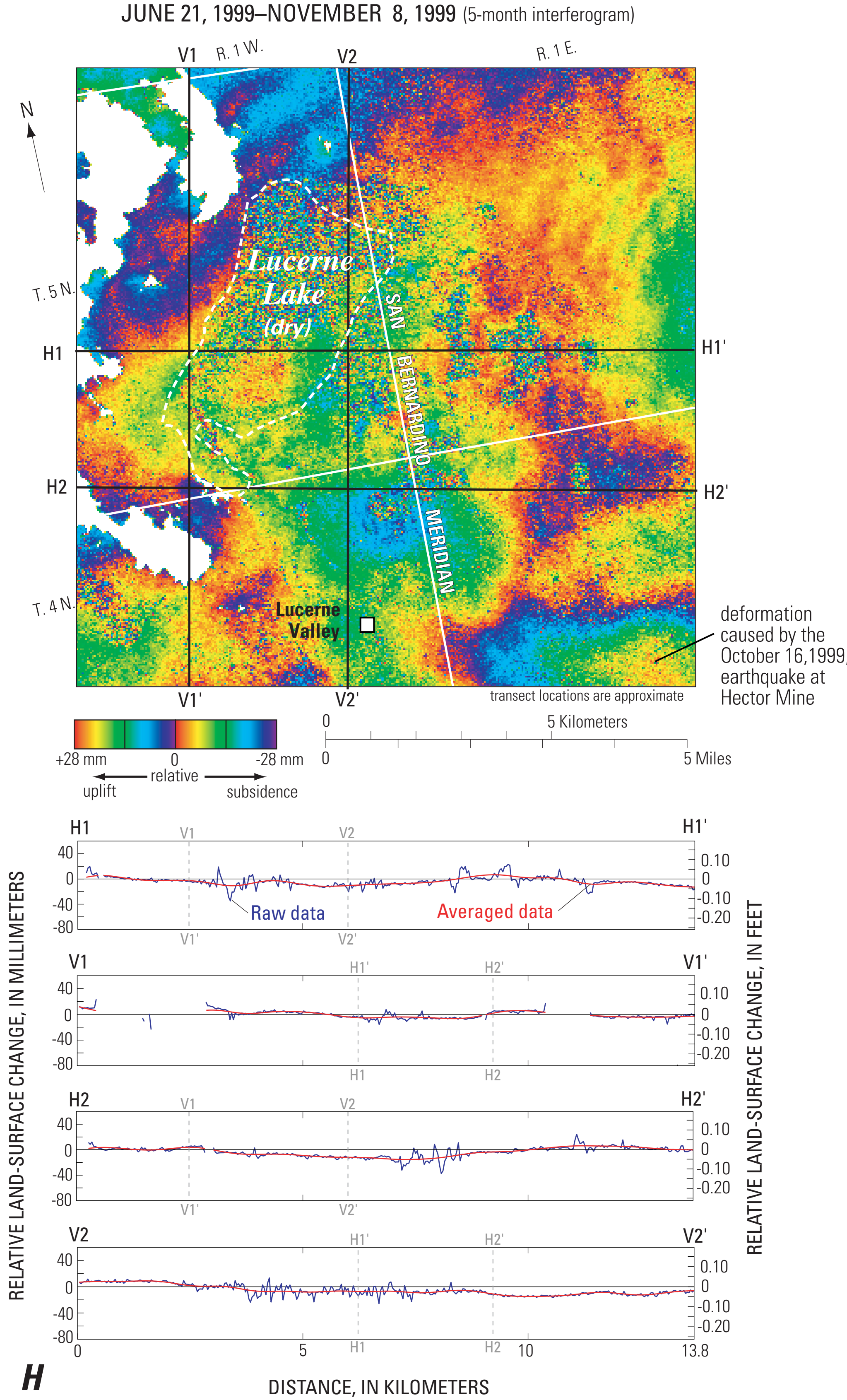

Figure 13.—Continued.

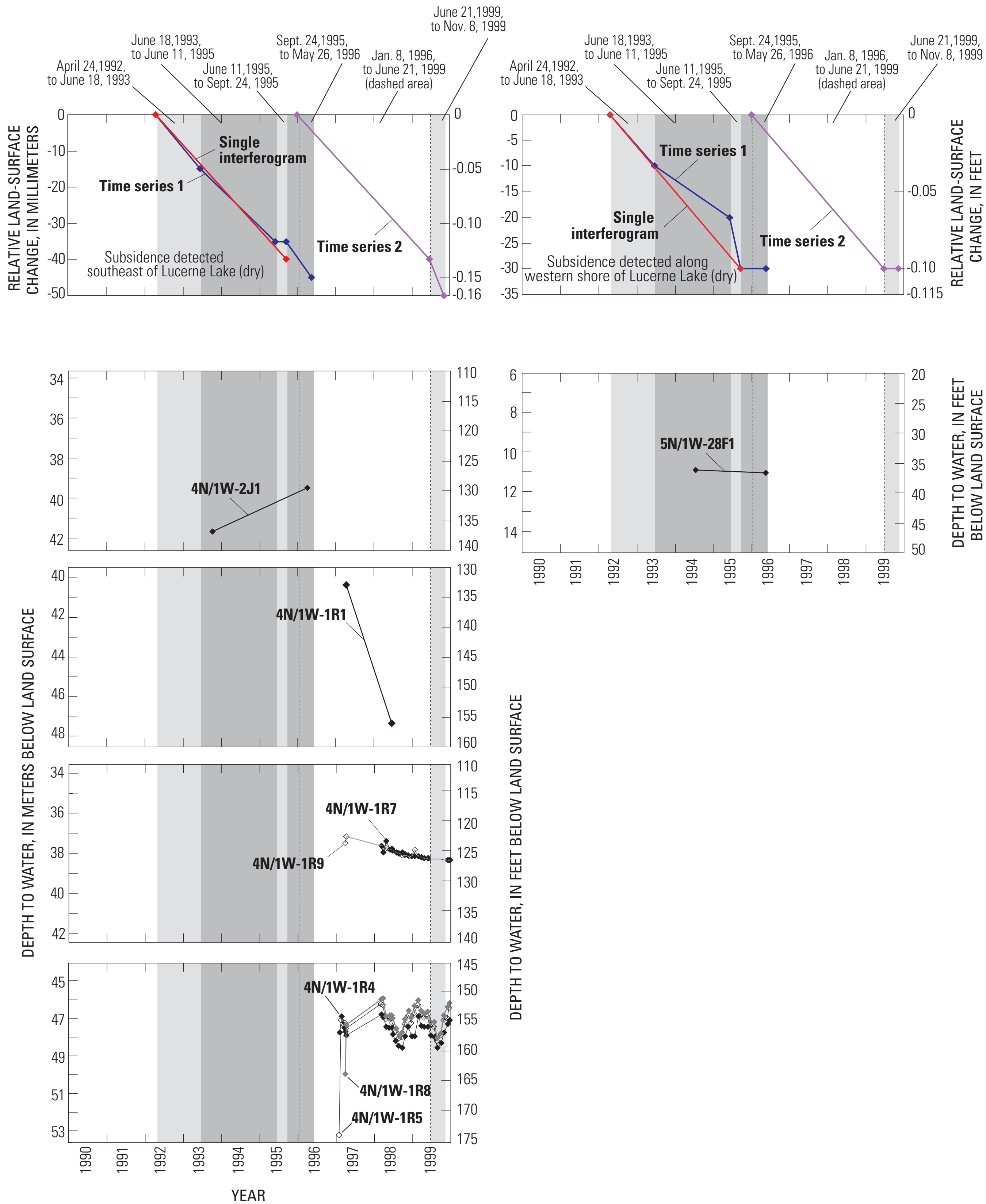

Figure 14. Depth to water for selected wells and piezometers and relative land-surface change in the Lucerne Valley area, San Bernardino County, California. (See figure 13*A* for locations of wells.)

The interferograms for the Lucerne Valley area indicate that an area southeast of Lucerne Lake (dry) subsided about 90 mm (0.3 ft) between April 24, 1992, and November 8, 1999 (fig. 14). The area of subsidence is near GPS stations RAIN and HOLM, where as much as 600 mm (2 ft) ± 1,500 (5 ft) of subsidence occurred between 1969 and 1998. Water-level data for wells in the area are sparse, especially prior to 1997, before the construction of and data collection for cluster wells 4N/1W-1R4–9. The apparent water-level rise in well 4N/1W-2J1 and decline in 4N/1W-1R1 may be due to seasonal effects and thus may not represent a longer term trend. Water levels in wells 4N/1W-1R7 and -1R9 declined linearly less than 1.5 m (5 ft) between 1997 and 1999; wells 4N/1W-1R4, -1R5, and -1R8 show a 1.5 to 3 m (5 to 10 ft) seasonal change for 1997–99, a slight decline from winter to winter, but almost no change from summer to summer (fig. 14; see figure 3 for screened intervals).

Although the limited amount of water-level data for the periods coincident with the interferograms hinders a meaningful analysis of a possible relation between ground-water levels in the 1990s and land subsidence, historical water-level data provide insights into the relation. Water levels in wells in the area declined 30 m (100 ft) between the 1950s and early 1990s as shown by the hydrographs for wells 5N/1W-25G1 and 5N/1E-17D1 in figure 5. In 1993, the adjudication began, requiring ground-water pumpage to be reduced by 20 percent (Stamos and others, 2001). As a result, ground-water levels southeast of Lucerne Lake (dry) rose and then stabilized (fig. 5). Stable ground-water levels and temporally coincident subsidence indicates that the fine-grained parts of the aquifer system may be compacting residually, still equilibrating with reduced pressures in the coarser grained parts of the aquifer system (fig. 3) caused by ground-water-level declines that occurred prior to 1993.

The interferograms for the Lucerne Valley area indicate that the area along the western shore of the lake subsided about 60 mm (0.2 ft) between April 24, 1992, and November 8, 1999 (fig. 14). Only one well, 5N/1W-28F1 (unknown screened interval), which had data for the 1990s, is near the area of subsidence along the western shore of Lucerne Lake (fig. 13*A*). Water levels in this well declined less than 0.15 m (0.5 ft) between 1994 and 1996 (fig. 14). Because of the limited amount of water-level data for periods coincident with the interferograms, a meaningful analysis of a possible relation between ground-water levels and InSAR-detected subsidence was not possible.

FUTURE MONITORING

The population of the southwestern Mojave Desert will undoubtedly continue to grow, thus increasing the demand for ground water. The demand on the ground-water resources will result in ground-water-level declines and, probably, continued or new land subsidence in some areas. Periodic land-subsidence monitoring will be needed to prevent the adverse affects of land subsidence.

InSAR can be used to develop spatially detailed seasonal, annual, or multi-year maps of ground displacements. Such maps can show changes as small as 5 mm (0.02 ft) in the vertical position of land surface (Hoffmann and others, 2001). In addition, the InSAR measurements could be compared with ground-water-level data to better define a possible relation between aquifer-system deformation (expressed as vertical changes at land surface) and changes in ground-water levels. The ground-water levels should be measured at least twice annually from depth-dependent or aquifer-dependent wells in areas where vertical land-surface changes occurred during 1992–99, as documented in this study. For future land-based surveys, modifications could be made to the existing GPS network in Lucerne Valley and (or) new GPS networks could be established in areas where the InSAR maps indicated areas of vertical land-surface changes, such as in the El Mirage and Newberry Springs areas. Future monitoring of the GPS network (or networks) combined with the InSAR maps could be used to provide ground truth for the more spatially detailed and higher resolution InSAR measurements. For the amounts of subsidence detected in the interferograms for the Lucerne Valley area, an interval of 3 to 5 years between GPS surveys may be appropriate for detecting measurable changes in the vertical position of monuments for changes that are significantly larger than the expected GPS measurement error (figs. 13 and 14).

CONCLUSIONS

Ground water has been the primary source of domestic, agricultural, and municipal water supplies in the Mojave Desert, California, since the early 1900s. Owing to increasing urbanization, demands on local water supplies have caused overdraft conditions in some areas of the Mojave River and Morongo ground-water basins and caused declines in water levels in some wells of more than 30 meters (100 feet) between the 1950s and the 1990s. These water-level declines have the potential to induce or renew land subsidence (the lowering of land-surface elevations) in these Mojave Desert ground-water basins.

Leveling data for the Lucerne Valley area have been available since as early as 1944. These data were used with 1998 Global Positioning System (GPS) data to determine the location, extent, and magnitude of vertical land-surface changes in Lucerne Valley in the Morongo ground-water basin. GPS measurements for three geodetic monuments in the GPS network indicate that about 600 millimeters (2 feet) [plus or minus 1,500 millimeters (5 feet)] of subsidence occurred southeast of Lucerne Lake (dry) during the two comparison periods (1969–98 and 1975–98) for this study but the GPS measurements for seven other monuments in the area indicated very little or no change in vertical position. Water levels in this area of subsidence declined about 15 meters (50 feet) during 1970–98; the water levels in many wells were at their lowest recorded levels during the 1990s. The relation between subsidence and the record low water levels suggests that the preconsolidation stress of the aquifer system may have been exceeded during this period and that compaction may be permanent in these areas.

Interferometric synthetic aperture radar (InSAR) methods were used to determine the location, extent, and magnitude of vertical land-surface changes in the Mojave River and Morongo ground-water basins for various time intervals between 1992 and 1999. The interferograms show subsidence ranging from 45 to 90 mm (0.15 to 0.3 ft) in four areas of these two ground-water basins—the El Mirage, Lucerne Valley, Newberry Springs, and Lockhart–Harper Lake (dry) areas.

Water-level data for the areas undergoing vertical land-surface changes (detected using InSAR) were examined to determine whether these changes may be related to aquifer-system deformation caused by ground-water-level changes. Because of the limited water-level data available, much of which was from wells with unknown screened intervals, and a lack of temporally coincident water-level and InSAR data, the relation between the ground-water-level changes and the vertical land-surface changes that occurred during 1992–99 could not be clearly defined for the four areas. However, in all four areas, water-level data indicate that water levels in the 1990s were near or below historically low levels. This decline in ground-water levels can cause land subsidence. In the Lucerne Valley area, about 90 mm (0.3 ft) of subsidence was measured between 1992 and 1999 in an area where ground-water levels declined 30 m (100 ft) between the 1950s and 1993 but stabilized in the mid and late 1990s. Stable ground-water levels and temporally coincident subsidence indicates that fine-grained parts of the aquifer system may be compacting residually, still equilibrating with reduced pressures in the coarser grained parts of the aquifer system caused by ground-water-level declines that occurred prior to 1993.

This study supports part of a cooperative program with the Mojave Water Agency to monitor water resources in the Mojave River and Morongo ground-water basins. Land-subsidence monitoring will continue to be an important component of this program because of continued reliance on ground water in these ground-water basins.

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