Ground Displacements Caused by Aquifer-System Water-Level Variations Observed Using Interferometric Synthetic Aperture Radar near Albuquerque, New Mexico

---

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

Water-Resources Investigations Report 02-4235

Prepared in cooperation with the

CITY OF ALBUQUERQUE

science for a changing world

Ground Displacements Caused by Aquifer-System Water-Level Variations Observed Using Interferometric Synthetic Aperture Radar near Albuquerque, New Mexico

By Charles E. Heywood, Devin L. Galloway, and Sylvia V. Stork

---

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 02-4235

Prepared in cooperation with the

CITY OF ALBUQUERQUE

Albuquerque, New Mexico
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
5338 Montgomery Blvd. NE, Suite 400
Albuquerque, NM 87109-1311

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
Denver, CO 80225-0286

Information regarding research and data-collection programs of the U.S. Geological Survey is available on the Internet via the World Wide Web. You may connect to the home page for the New Mexico District Office using the URL *http://nm.water.usgs.gov.*

CONTENTS

	Page
Abstract	1
Introduction	1
Purpose and scope	3
Methods	3
Acknowledgments	3
Radar interferometry	3
Ground-displacement observations	4
793-day interferogram (July 2, 1993 - September 3, 1995)	4
Rio Rancho	4
Albuquerque	4
211-day interferogram (September 3, 1995 - April 1, 1996)	12
Rio Rancho	12
Albuquerque	12
1,004-day interferogram (July 2, 1993 - April 1, 1996)	12
Rio Rancho	12
Albuquerque	12
385-day interferogram (February 10, 1997 - March 2, 1998)	12
Rio Rancho	12
Albuquerque	12
560-day interferogram (March 2, 1998 - September 13, 1999)	12
Rio Rancho	13
Albuquerque	13
Other measurements	13
Correlation with ground-water-level changes	13
Geologic structures in the study area that influence ground-water flow	15
Conclusions	16
Selected references	16

FIGURES

1. Map showing area of interferogram coverage in the Albuquerque Basin, central New Mexico ... 2
2. Maps showing:
   A. Interferogram (793 day) showing ground displacement from July 2, 1993, to September 3, 1995 ... 5
   B. Interferogram (211 day) showing ground displacement in relation to mapped faults from September 3, 1995, to April 1, 1996 ... 6
   C. Interferogram (1,004 day) showing ground displacement from July 2, 1993, to April 1, 1996 ... 7
   D. Interferogram (385 day) showing ground displacement from February 10, 1997, to March 2, 1998 ... 8
   E. Interferogram (560 day) showing ground displacement from March 2, 1998, to September 13, 1999 ... 9
3. Graphs showing vertical displacement along profile A-A' from July 2, 1993, to September 13, 1999 ... 10
4. Graphs showing vertical displacement along profile B-B' from July 2, 1993, to September 13, 1999 ... 11
5. Graphs showing depth to water in:
   A. Garfield piezometers ... 14
   B. Del Sol Divider piezometers ... 14

TABLE

1. Selected synthetic aperture radar (SAR) data acquisitions and interferometric pairs ... 3

CONVERSION FACTORS, ABBREVIATIONS, AND DATUMS

Multiply	By	To obtain
millimeter (mm)	25.4	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.621	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
square kilometer (km^2)	247.1	acre

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Vertical Datum of 1983 (NAD 83).

GROUND DISPLACEMENTS CAUSED BY AQUIFER-SYSTEM WATER-LEVEL VARIATIONS OBSERVED USING INTERFEROMETRIC SYNTHETIC APERTURE RADAR NEAR ALBUQUERQUE, NEW MEXICO

By Charles E. Heywood, Devin L. Galloway, and Sylvia V. Stork

ABSTRACT

Six synthetic aperture radar (SAR) images were processed to form five unwrapped interferometric (InSAR) images of the greater metropolitan area in the Albuquerque Basin. Most interference patterns in the images were caused by range displacements resulting from changes in land-surface elevation. Loci of land-surface elevation changes correlate with changes in aquifer-system water levels and largely result from the elastic response of the aquifer-system skeletal material to changes in pore-fluid pressure. The magnitude of the observed land-surface subsidence and rebound suggests that aquifer-system deformation resulting from ground-water withdrawals in the Albuquerque area has probably remained in the elastic (recoverable) range from July 1993 through September 1999. Evidence of inelastic (permanent) land subsidence in the Rio Rancho area exists, but its relation to compaction of the aquifer system is inconclusive because of insufficient water-level data. Patterns of elastic deformation in both Albuquerque and Rio Rancho suggest that intrabasin faults impede ground-water-pressure diffusion at seasonal time scales and that these faults are probably important in controlling patterns of regional ground-water flow.

INTRODUCTION

Permanent land subsidence caused by the inelastic compaction of overdrafted alluvial aquifer systems is a global problem. In many ground-water basins in the arid to semiarid Western United States, permanent regional-scale subsidence has resulted from mining ground water for agricultural, municipal, and industrial water supplies (Galloway and others, 1999). Notable examples are the Antelope (Mojave Desert) (Ikehara and Phillips, 1994; Galloway and others, 1998; Sneed and Galloway, 2000), Santa Ana (Bawden and others, 2001), San Joaquin (Poland and others, 1975), and Santa Clara (Poland and Ireland, 1988; Ikehara and others, 1998) Valleys in California; the Las Vegas Valley (Bell, 1981a,b; Bell and Price, 1993; Amelung and others, 1999; Hoffman and others, 2001) in Nevada; and several basins in south-central Arizona (Laney and others, 1978; Carpenter, 1999). Presently, the maximum historical subsidence in these basins ranges from about 2 to 9 m. In each of these examples, large volumes of ground water extracted to irrigate crops and supply municipal-industrial demands caused ground-water levels to decline below critical thresholds, leading to the onset of subsidence. Conjunctive use of local ground-water supplies and imported surface-water supplies has helped decrease or halt permanent subsidence in each of these basins.

Short of permanent subsidence, non-permanent, reversible, elastic deformation occurs in all aquifer systems subject to pore-fluid-pressure variations. From other alluvial basins subjected to daily and seasonal pumping stresses where aquifer-system deformation has been studied and monitored, we know that these elastic displacements are typically about 1 mm for daily periods and can exceed 30–50 mm for seasonal periods.

In the Albuquerque area, a network of 44 benchmarks was established in 1993, which was surveyed using the Global Positioning System (GPS) in March-April 1993 and again in August 1994. In the 16 months between these surveys, no benchmark elevation changes greater than 1.3 cm were detected, which was the accuracy limit of the GPS survey technique.

Data collected between December 1994 and March 2002 at a 315-m-deep borehole extensometer in the Rio Grande Valley near Albuquerque (Heywood, 1998) indicate that aquifer-system deformation was predominantly elastic, with less than 2 mm of permanent compaction over that period. Geomorphic evidence suggests that the Rio Grande has eroded as much as 100 m of sediment of Pleistocene age from a pre-existing fluvial-alluvial plain, of which the present Llano de Albuquerque (fig. 1) is a relict. Underlying sediment was preconsolidated by the weight of the sedimentary overburden; subsequent erosion of the overburden resulted in overconsolidation of these sediments. This overconsolidation suggests that aquifer-system deformation resulting from ground-water-level declines is likely to remain in the elastic range until such declines cause aquifer-system

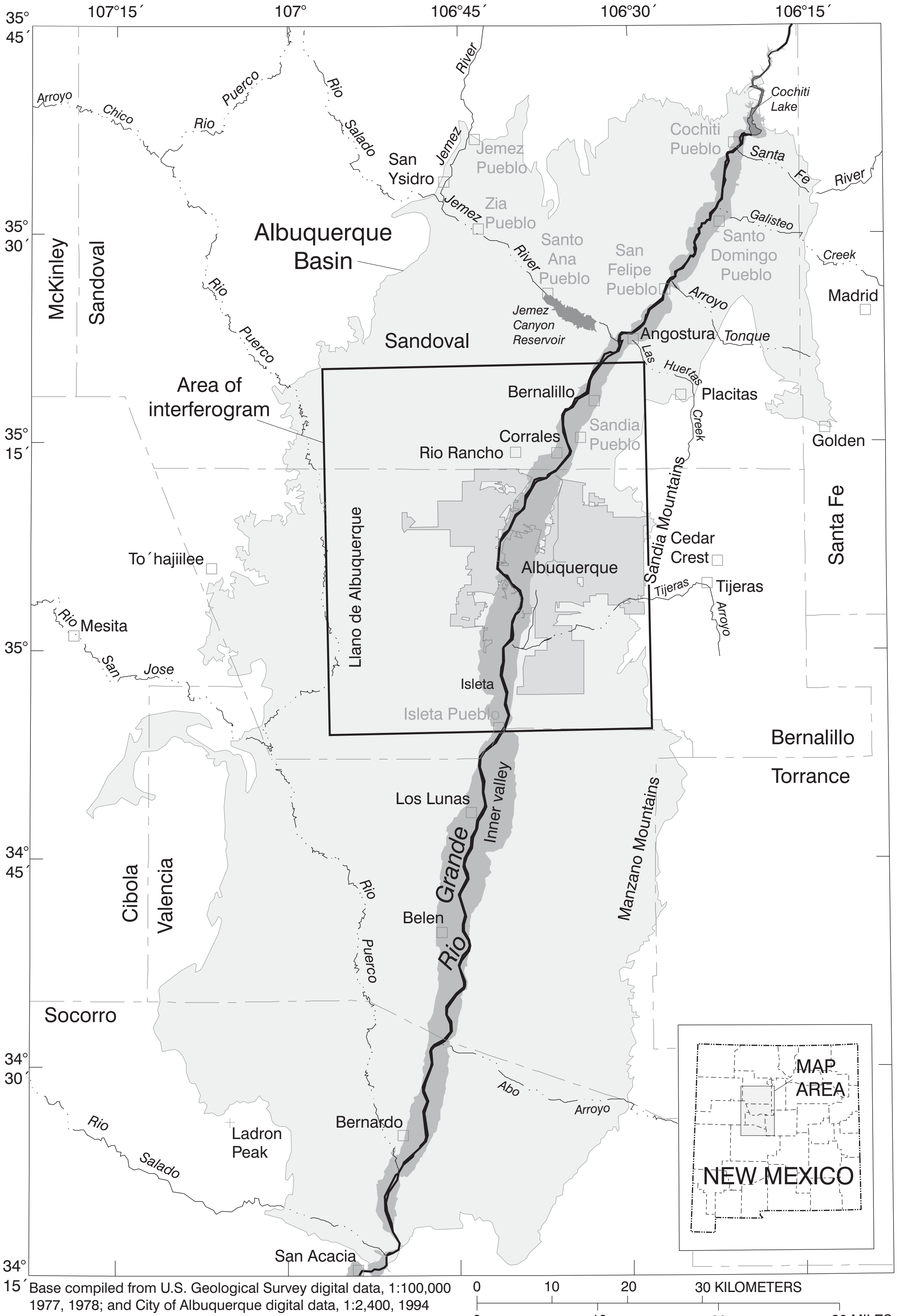


Figure 1. Area of interferogram coverage in the Albuquerque Basin, central New Mexico.

effective stresses to exceed the preconsolidation stress levels. The magnitude of water-level decline required to exceed these levels can be estimated using simple assumptions (Terzaghi, 1925). By assuming similar depths to the paleowater and modern water tables, an average grain density of 2.7 grams/cm^3, and porosity of 0.3, the equivalent water-level decline is approximately 1.2 times the thickness of the missing overburden, or about 120 m. By 1996, ground-water levels had declined as much as 50 m from steady-state conditions in some areas of Albuquerque (Bartolino and Cole, 2002).

Purpose and Scope

This report presents the results of a study to determine potential land-surface displacement in and near Albuquerque, New Mexico. Interferometric synthetic aperture radar (InSAR) data were obtained to help detect small-scale deformation of the aquifer system resulting from water-level variations. Five interferograms are presented for selected time intervals from July 1993 to September 1999.

Methods

InSAR was used to obtain spatially detailed maps of ground-surface displacements for purposes of detecting small-scale deformation of the aquifer system in the upper Albuquerque Basin. This technique has been successfully applied to investigations of crustal deformation caused by earthquakes (Massonnet and others, 1993; Peltzer and others, 1999), volcanoes (Massonnet and others, 1995; Wicks and others, 1998), and land subsidence related to the withdrawal of subsurface fluids for geothermal energy (Massonnet and others, 1997), oil and gas production (Fielding and others, 1998), and ground-water resources (Galloway and others, 1998, 2000; Amelung and others, 1999; Hoffman and others, 2001).

Acknowledgments

This study was partially funded through a cooperative agreement between the U.S. Geological Survey (USGS) and the City of Albuquerque. Radar data for this study were obtained from the European Space Agency, distributed through Eurimage Corporation for purposes of research and development.

RADAR INTERFEROMETRY

Five interferograms were processed using SAR data (Track 98, Frame 2907) acquired by the European Remote Sensing (ERS) satellites, ERS-1 and ERS-2, operated by the European Space Agency. Six SAR scenes with similar acquisition geometries (absolute value of the orbital perpendicular baselines less than 150 m) were paired to form five interferograms covering the period July 2, 1993, to September 13, 1999 (table 1). Interferometric processing was done on a subarea of the full SAR frame to focus on the Albuquerque area (fig. 1). To eliminate some of the noise in the interferograms, the SAR images were averaged, resulting in a 40-m resolution in both azimuth (along track) and range (across track) directions.

Table 1. Selected synthetic aperture radar (SAR) data acquisitions and interferometric pairs

[--, no data]

SAR data			Interferometric pairs		
Satellite[1]	Image date	Orbit number	Orbital pair	Orbital perpen-dicular baseline, in meters	Time span, in days
ERS-1	7/2/1993	10263	10263-21629	45	793
ERS-1	9/3/1995	21629	21629-4962	-39	211
ERS-2	4/1/1996	4962	10263-4962	6	1,004
ERS-2	2/10/1997	9471	9471-14982	147	385
ERS-2	3/2/1998	14982	14982-22998	33	560
ERS-2	9/13/1999	22998	--	--	--

[1]European Remote Sensing (ERS) satellites operated by the European Space Agency.

The phase component of the complex-valued interferogram contains information not only about coherent displacements of reflectors imaged by the radar, but also topography and propagation delays due to spatially and temporally variable tropospheric water content. The effects of topography were removed by simulating a topographic interferogram in the geometry of the SAR scenes using a 30-m digital elevation model (DEM) of the study area and subtracting it from each. The effect of variable tropospheric delays was minimized by selecting SAR scenes acquired during periods of dry weather based on local meteorological data. To calculate the interferograms, we used the PRISME/DIAPASON software (Centre National d'Etudes Spatiales, 1997) in the two-pass approach described by Massonnet and others (1994) and Massonnet and Feigl (1998).

The coherent phase component of the resulting interferograms represents range (line-of-sight) displacements, mapped modulo 2 Pi (or 28 mm, one-half the wavelength of the C-band radar). Prior to unwrapping, the interferogram values were smoothed using a spectral smoothing algorithm (Z. Lu, U.S. Geological Survey, written commun., 2000). The smoothed interferograms were unwrapped using *Escher*, an algorithm (Shindle, 1999) that employs the branch-cut method (Goldstein and others, 1988). The resulting interferograms were transformed from the geometry of the radar to cartographic coordinates (Lambert central meridian = -106 degrees), resampled at 30-m resolution on the registered grid of the DEM.

By assuming that all the observed range displacement was due to vertical ground displacements, the vertical component of the displacement field was computed from the range displacements using the 23-degree radar incident angle (Hanssen, 2001). Interferogram values were verified in areas of known bedrock outcrop or insignificant alluvial thickness near the west flank of the Sandia Mountains (fig. 2), which were presumed to be stable over the period spanned by the interferogram. Values in the 793-day interferogram (fig. 2A) were decreased by 5.575 mm to indicate zero displacement over bedrock. The interferograms are shown in color draped over a gray-scale shaded-relief image of the area in figure 2A-2E. (Areas in which the interferogram could not be unwrapped are transparent in these figures, thereby providing geographic reference from the underlying shaded relief image.) The interferogram values were smoothed with a 5 x 5 pixel-averaging filter prior to generating the displacement profiles (fig. 2).

GROUND-DISPLACEMENT OBSERVATIONS

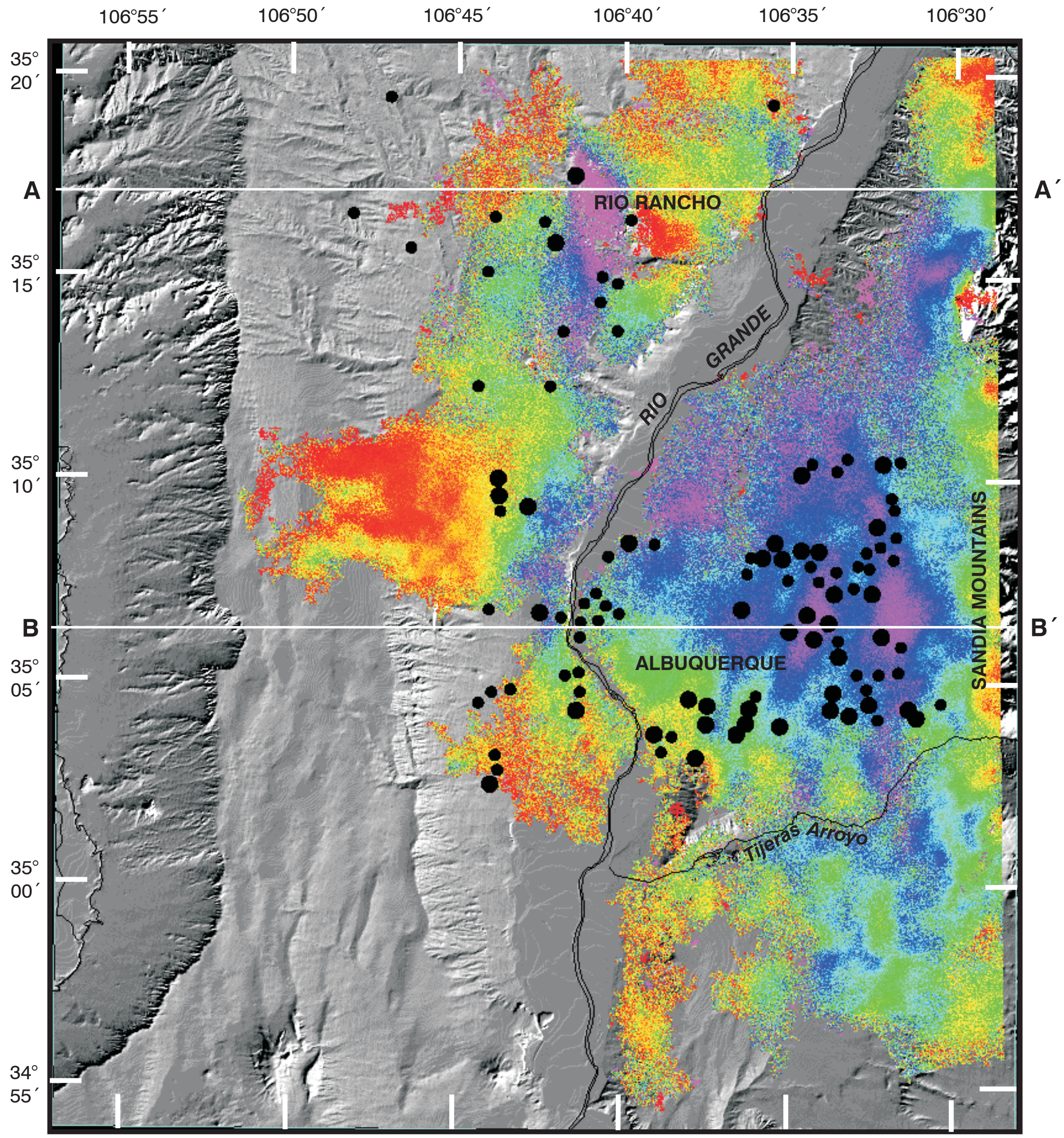
793-Day Interferogram (July 2, 1993 - September 3, 1995)

Rio Rancho

Maximum subsidence of about 48 mm occurs in Rio Rancho near 35°17'N., 106°42'W. The area that has subsided more than 7.6 mm (magenta in fig. 2A) covers about 12 km^2. Rectilinear boundaries on the northeast and western margins and more diffuse, less well defined boundaries on the southern and southeastern margins delimit the subsided area. The linear west and northeast boundaries roughly parallel the strikes of mapped faults, shown in figure 2B, about 1 km distant from each boundary. The gradient of displacement along profile A-A' (fig. 3) at these boundaries is relatively large, nearly 1.0×10^{-5} on the northeast and possibly larger on the west, where signal decorrelation prevented unwrapping of the interferogram and gradient calculation.

Albuquerque

Subsidence of 10 to 15 mm in the Albuquerque region extends from about 5 km west of the Rio Grande to longitude 106°30'W. near the Sandia Mountains at the eastern margin of the interferogram (fig. 2A), and from latitude 35°17'N. on the north to 35°3'N. on the south. Patterns of displacement are distinctive in the subsided area. An extended line along the strike of the northeastern boundary of the Rio Rancho subsidence bowl coincides with a northeastern subsidence boundary in Albuquerque. Two to three northeastern-trending elongate subsidence lobes with relative displacement of about 6 mm create an undulating displacement surface across the region; the troughs of two prominent undulations are evident in profile B-B' (fig. 4). Alternatively, these apparent northeast-trending subsidence lobes could be tropospheric artifacts; signal delays in the September 3, 1995, SAR data would appear as subsidence in this interferogram. East of the Rio Grande, near latitude 35°9'N., longitude 106°39'W., a localized, circular-shaped signal has relative subsidence of about 15 mm. An elliptical-shaped feature at latitude 35°15'N., longitude 106°31'W. has a maximum subsidence of 13 mm.



U.S. Geological Survey
digital elevation data

0 5 10 15 20 25 KILOMETERS

0 5 10 15 20 25 MILES

EXPLANATION

● Well producing less than 1,000 acre-feet per year from January to August 1995

● Well producing greater than 1,000 acre-feet per year from January to August 1995

A-A´, B-B´ Trace of profiles shown in figure 3

Change in land-surface elevation, in millimeters

68 29 10 7 4 2 0 -1.8 -3.5 -5.1 -7.5 -68

Uplift ⟷ Subsidence

Figure 2A. Interferogram (793 day) showing ground displacement from July 2, 1993, to September 3, 1995.

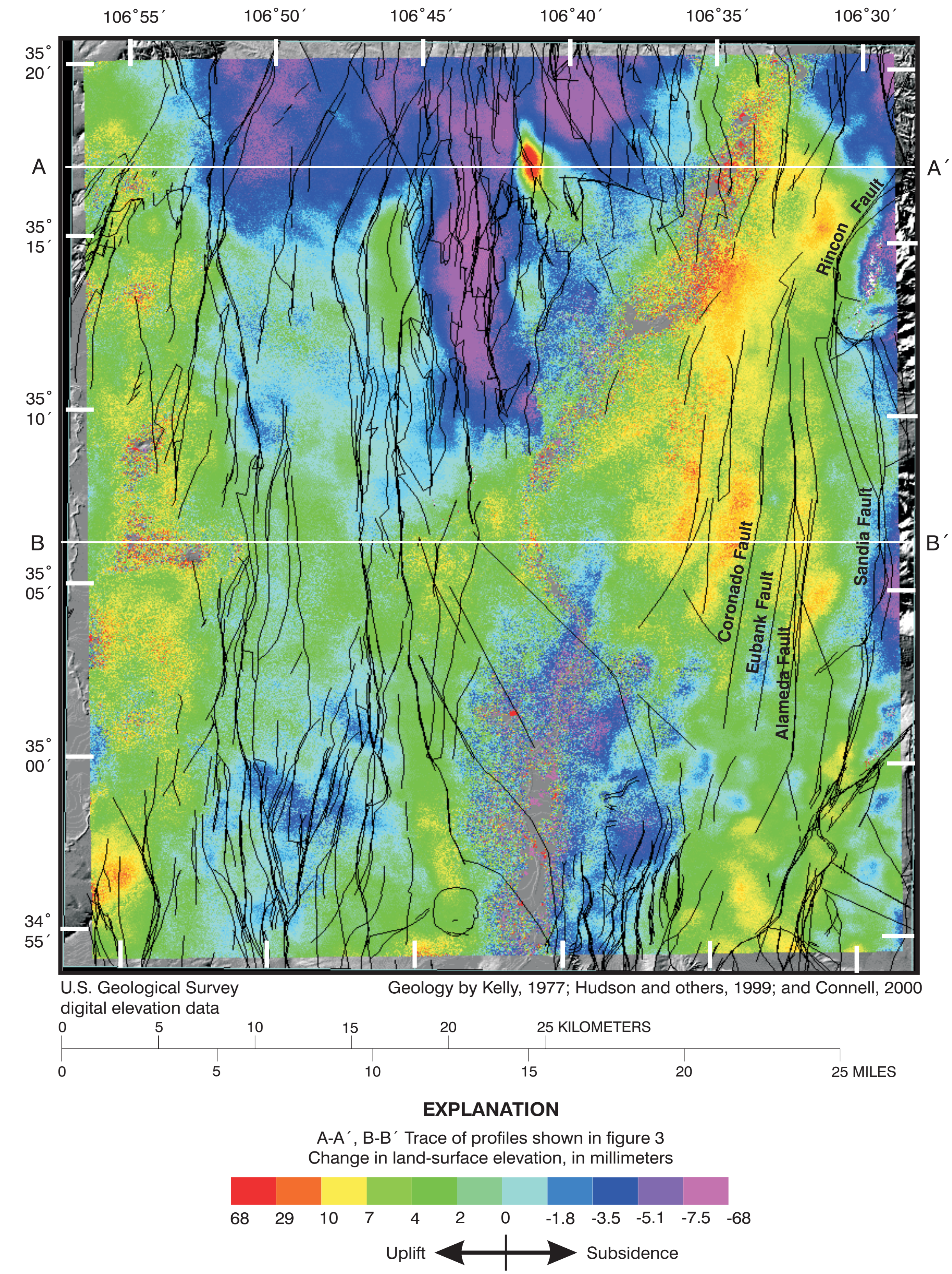


Figure 2B. Interferogram (211 day) showing ground displacement in relation to mapped faults from September 3, 1995, to April 1, 1996.

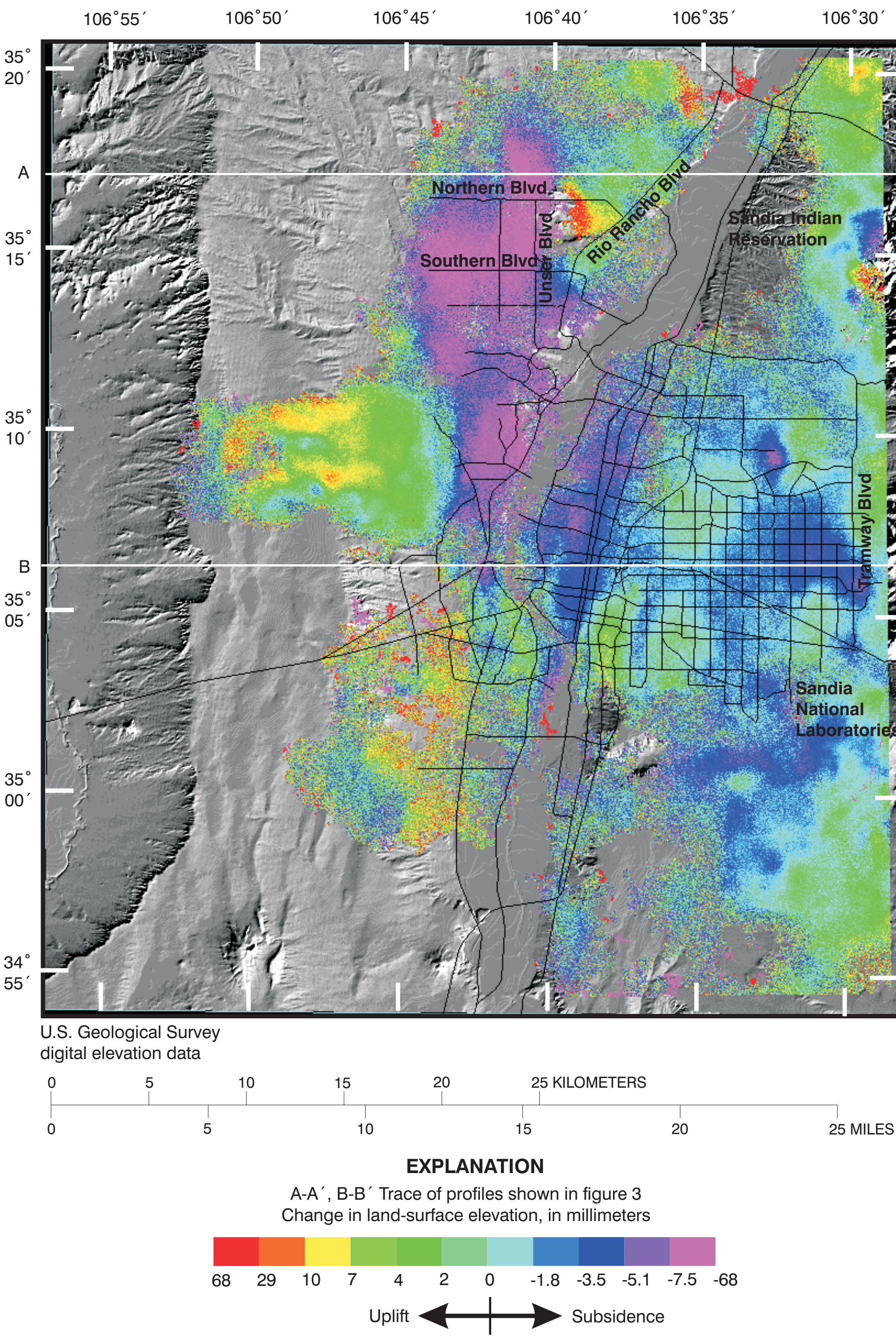


Figure 2C. Interferogram (1,004 day) showing ground displacement from July 2, 1993, to April 1, 1996.

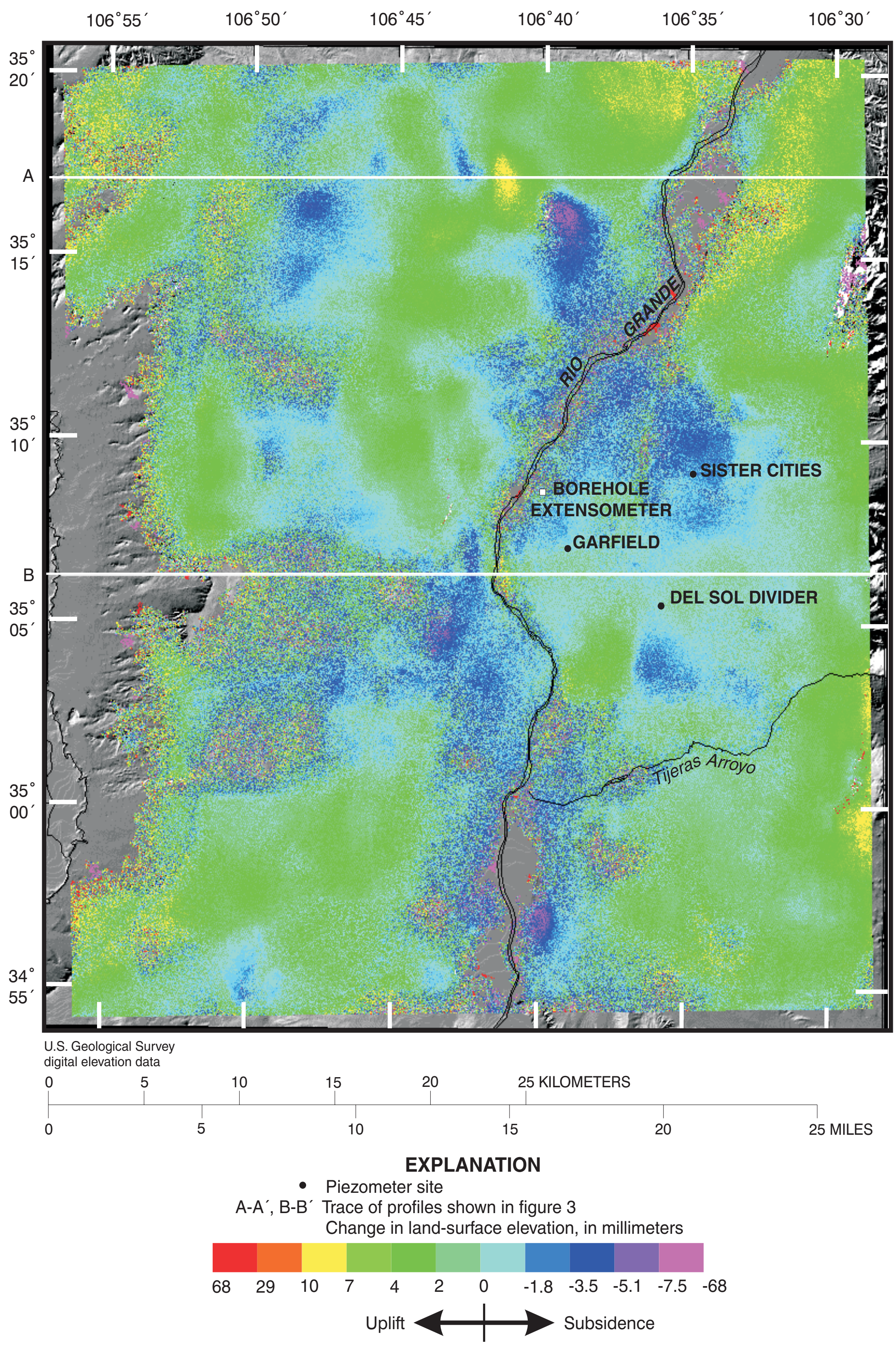


Figure 2D. Interferogram (385 day) showing ground displacement from February 10, 1997, to March 2, 1998.

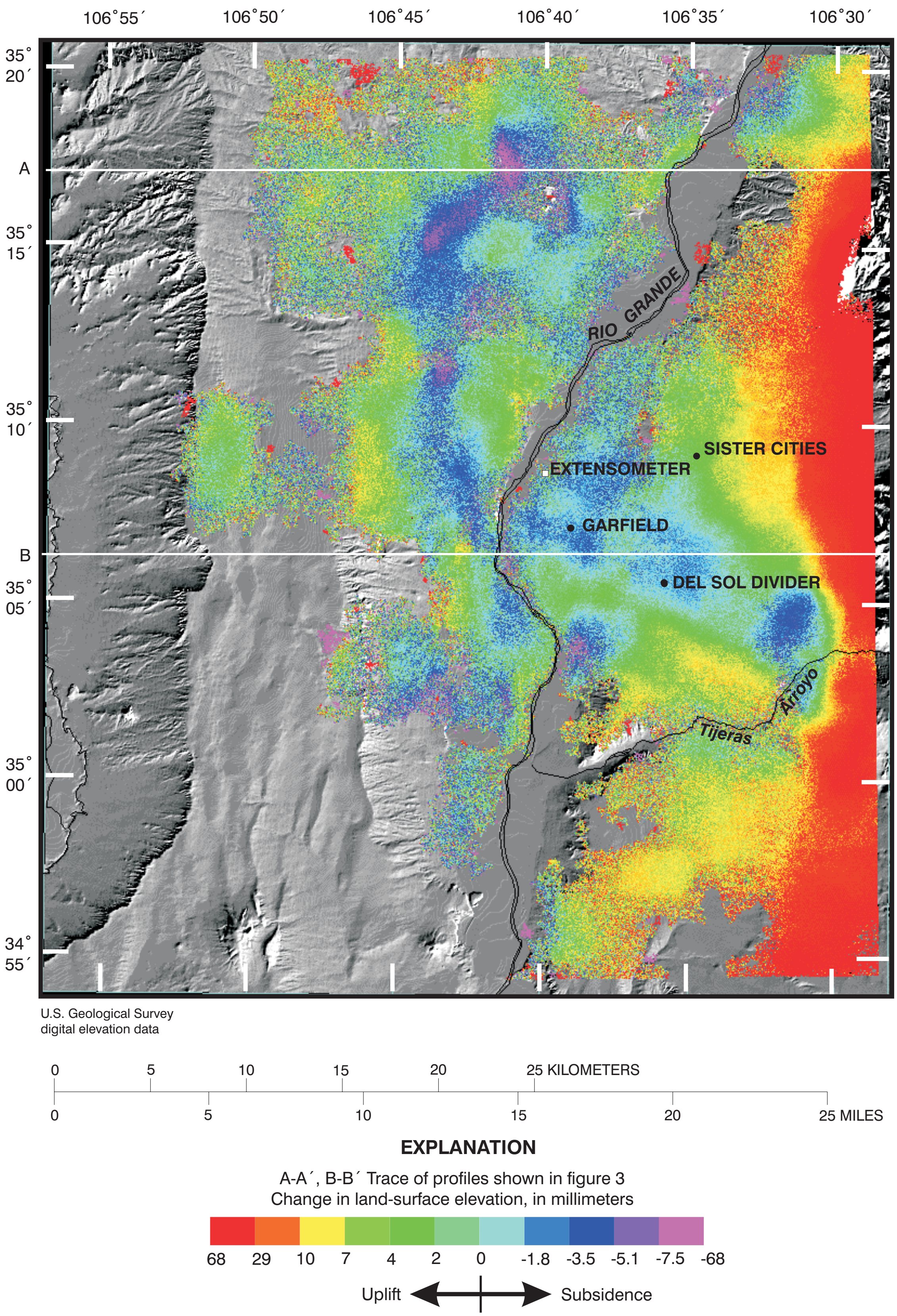


Figure 2E. Interferogram (560 day) showing ground displacement from March 2, 1998, to September 13, 1999.

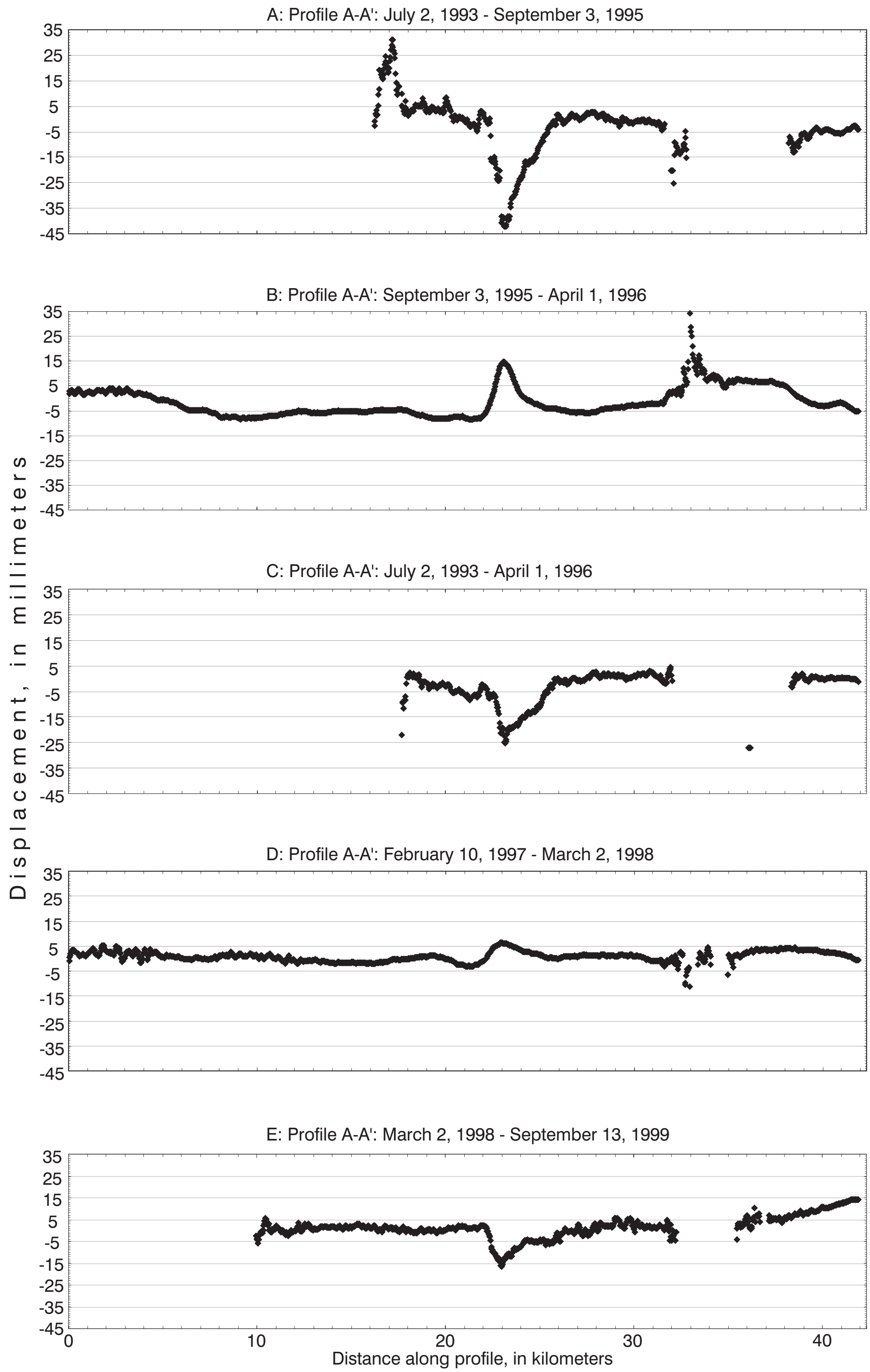


Figure 3. Vertical displacement along profile A-A´ from July 2, 1993, to September 13, 1999. Trace of profile in figure 2A-2E.

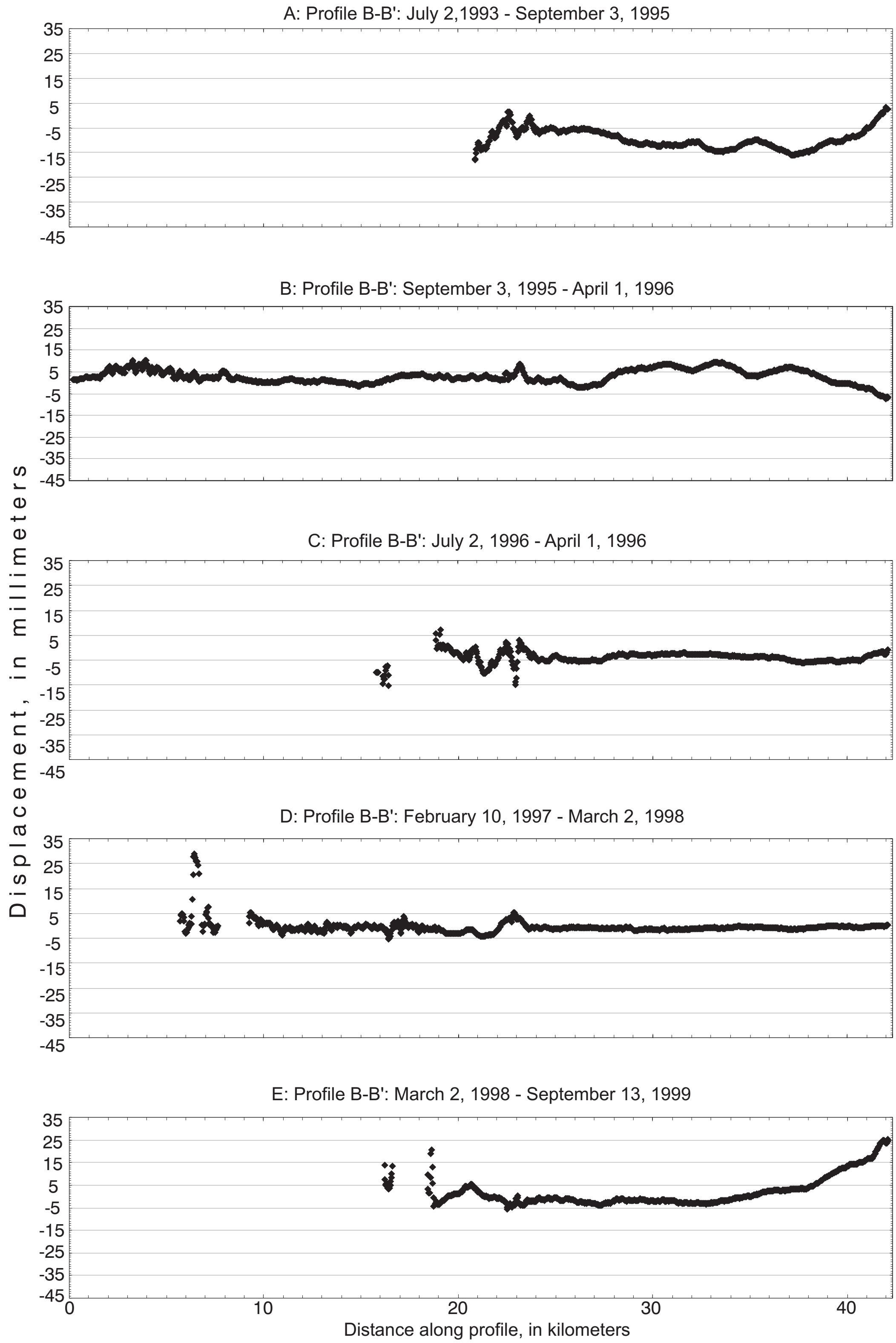


Figure 4. Vertical displacement along profile B-B´ from July 2, 1993, to September 13, 1999. Trace of profile in figure 2A-2E.

211-Day Interferogram (September 3, 1995 - April 1, 1996)

Rio Rancho

An uplift of magnitude 24 mm (fig. 2B) is observed in the location of the prominent subsidence zone on the 793-day interferogram (fig. 2A). The gradient of displacement measured along profile A-A' (fig. 3) across the western and northeastern boundaries is -2.6×10^{-5} and -7.8×10^{-6}, respectively. The good coherence of this image reveals a linear boundary along the eastern portion of the uplift feature (yellow fringe along profile A-A' in fig. 2B), which is subparallel to the western boundary of the uplift feature. This uplift zone has a quadrilateral shape, similar to the spatially coincident subsidence zone on the 793-day interferogram.

An elongate subsidence feature near longitude 106°43'W. (blue and magenta-purple pattern in fig. 2B) extends south to latitude 35°10'N. The eastern boundary of this prominent south-trending lobe conforms to the mapped location of south-trending faults (fig. 2B). The gradients of displacement from the lobe margins to the location of maximum subsidence are smaller (1.9×10^{-6} and 3.9×10^{-6}, respectively; fig. 3) than those of the rectilinear feature described earlier. The southern portion of this lobe also appears as subsidence in the 793- and 1,004-day interferograms (fig. 2A,2C). To the west, a south-trending zone (green) indicates uplift of about 5 mm (fig. 2B). This area could not be unwrapped in the 793-day or 1,004-day interferograms.

Albuquerque

The undulating displacement surface observed in Albuquerque in the 793-day interferogram (fig. 2A) appears with reverse sense: subsidence troughs have become uplift ridges (fig. 2B). The apparent northeast-trending uplift ridges corresponding to the subsidence lobes observed in figure 2A could be tropospheric artifacts: signal delays in the September 3, 1995, SAR data would appear as uplift in this interferogram. The elliptical-shaped feature at latitude 35°15'N., longitude 106°31'W. observed in the 793-day interferogram now appears as 13 mm of uplift. Some subsidence is observed at latitude 35°17'N., longitude 106°39'W. The gradient of displacement along profile B-B' is presented in figure 4.

1,004-Day Interferogram (July 2, 1993 - April 1, 1996)

Rio Rancho

Prominent features in this interferogram are similar locations to those described for the 793-day interferogram. A maximum of 21 mm of subsidence occurs near the center of the quadrilateral-shaped feature in figures 2C and 3. To the southwest, a broad feature with as much as 14 mm of subsidence extends nearly 5 km east to west. Displacement gradients on the margins of this feature average 2.0×10^{-6} (fig. 2C).

Albuquerque

The undulating displacement surface and other features observed in the 793- and 211-day interferograms are not obvious in figures 2C and 4. West of Tramway Boulevard, near latitude 35°9'N., longitude 106°33'W., a localized signal with 8 mm of subsidence is evident. Subsidence west of the Rio Grande near latitude 35°9'N., longitude 106°W. is about 10-15 mm.

385-Day Interferogram (February 10, 1997 - March 2, 1998)

Rio Rancho

The quadrilateral-shaped feature previously discussed (fig. 2B) is discernible with small magnitude uplift (yellow) in figures 2D and 3. Minor subsidence is observed at latitude 35°16'N., longitude 106°39'W. The sense of deformation for each of these features is opposite that observed in the 793- and 1,004-day interferograms.

Albuquerque

Little net displacement occurred in the Albuquerque area during this nearly 1-year period.

560-Day Interferogram (March 2, 1998 - September 13, 1999)

Atmospheric artifacts that were evident in the southwestern and northwestern corners of this interferogram were removed and appear transparent in figure 2E. The area shaded red along the east side is topographically related and may be due to decreasing density of uplifted air. Good coherence was obtained over most of the Albuquerque and Rio Rancho areas.

Rio Rancho

Subsidence features observed in the previous four interferograms (fig. 2A-2D) are presented in figures 2E and 3, albeit with smaller magnitudes.

Albuquerque

Minor displacement (less than 5 mm) is observed over most of Albuquerque. An uplift feature trending west-northwest near Tijeras Arroyo and a localized subsidence area just east of the Rio Grande at latitude 35°4'N. (purple) are possible exceptions.

Other Measurements

A borehole extensometer east of the Rio Grande (fig. 2D) in Albuquerque (Heywood, 1997, 1998) measures compaction in the interval 5-315 m below land surface. At the extensometer site, completed in December 1994, a continuous-analog compaction time series and discrete 15-minute digital compaction and associated piezometric time series are recorded. The displacement time history at the extensometer shows 1-mm-level daily and seasonal variations in response to water-level variations at a nearby production well. For the time corresponding to the 211-day interferogram (fig. 2B), accounting for the 1748-hour Greenwich Mean Time (GMT) orbital pass-over, 1.7 mm of uplift was measured on the extensometer. The interferometrically derived displacement in the pixel containing the extensometer is 2.1 mm of uplift; averaging of 2 x 2 pixels and 4 x 4 pixels centered on the extensometer site gives 1.3 and 1.4 mm of uplift, respectively. The other interferograms were similarly compared to the extensometric data.

The USGS and City of Albuquerque installed a geodetic land-subsidence monitoring network in 1993, which was surveyed with the GPS in 1993 and 1994. For 1993-94, the maximum computed benchmark elevation change of -2 cm was observed near a well in Rio Rancho. Other computed benchmark elevation changes were less than 2 cm, which was considered the limit of resolution of the differential GPS survey. The time span between the GPS surveys is less than, and contained within, the period of the first (793-day) interferogram. The negligible vertical displacements measured at discrete benchmarks using GPS over 1993-94 agree with those in the 793-day interferogram.

Correlation with Ground-Water-Level Changes

Ground-water levels in the Albuquerque area exhibit annual periodicity superimposed on a long-term decline. Hydrographs of selected piezometers (fig. 5A,5B) reveal that deep ground-water levels (that is, in wells screened more than 100 m below the water table) recover during the autumn and early winter months and typically attain their maximum levels in January and February. Deep ground-water levels decline during spring and early summer months and typically reach minimum levels in July and August. Seasonal variations in municipal ground-water pumping contribute to this cyclic response. Land-surface elevation changes observed in the interferograms (fig. 2A-2E) follow these trends in deep ground-water-level changes. This spatial and temporal correspondence suggests that observed apparent land-surface elevation changes result from elastic compression and expansion of the aquifer-system skeletal matrix resulting from pore-fluid-pressure changes.

At the Garfield piezometer site (figs. 2D, 5A) in the Rio Grande Valley, seasonal variations of the water table and deeper water levels are out of phase. The higher water table increases the geostatic load and hence the effective stress and consequent aquifer-system skeletal matrix compression in the deeper zones hydraulically separated from the water table. Relative to in-phase variations, this out-of-phase relation between the water table and deeper water levels should accentuate the aquifer-system compression resulting from a given magnitude of water-level change.

The 793-day interferogram (July 2, 1993, to September 3, 1995; fig. 2A) corresponds to a period during which net annual ground-water levels declined relatively rapidly in the Albuquerque and Rio Rancho areas. Few water-level observation piezometers existed in the area at that time, but water-level records for Albuquerque production wells indicate that annual declines were about 1-2 m per year. Two seasonal periods of water-level recovery are encompassed in this interferogram, during which ground water flowed locally toward the loci of previous extractions. The observed subsidence features are therefore biased toward ground-water extractions that occurred during the final period of seasonal water-level declines. To enhance correlation between ground-water extraction and subsidence, extractions from ground-water supply wells were totaled for January through August 1995 and are shown in figure 5A.

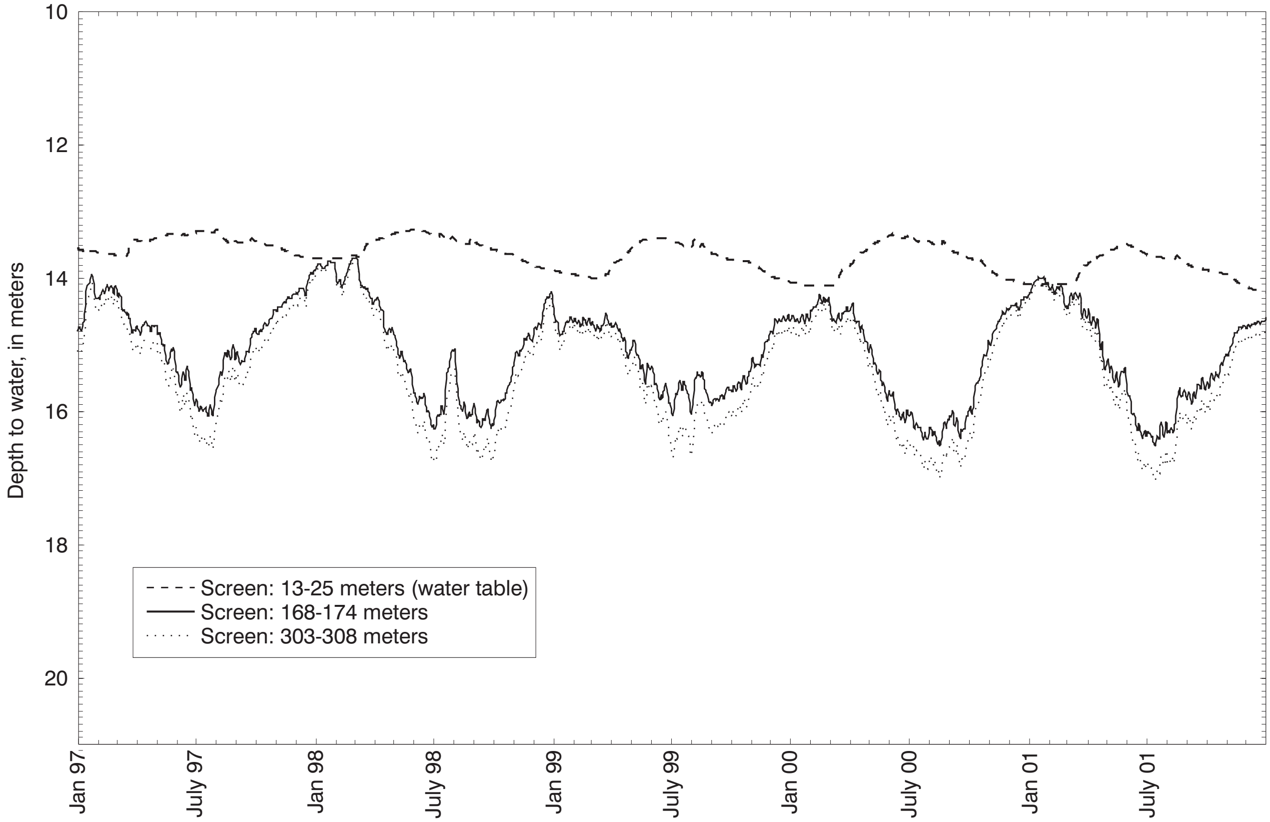


Figure 5A. Depth to water in Garfield piezometers. Location of piezometer site in figure 2D.

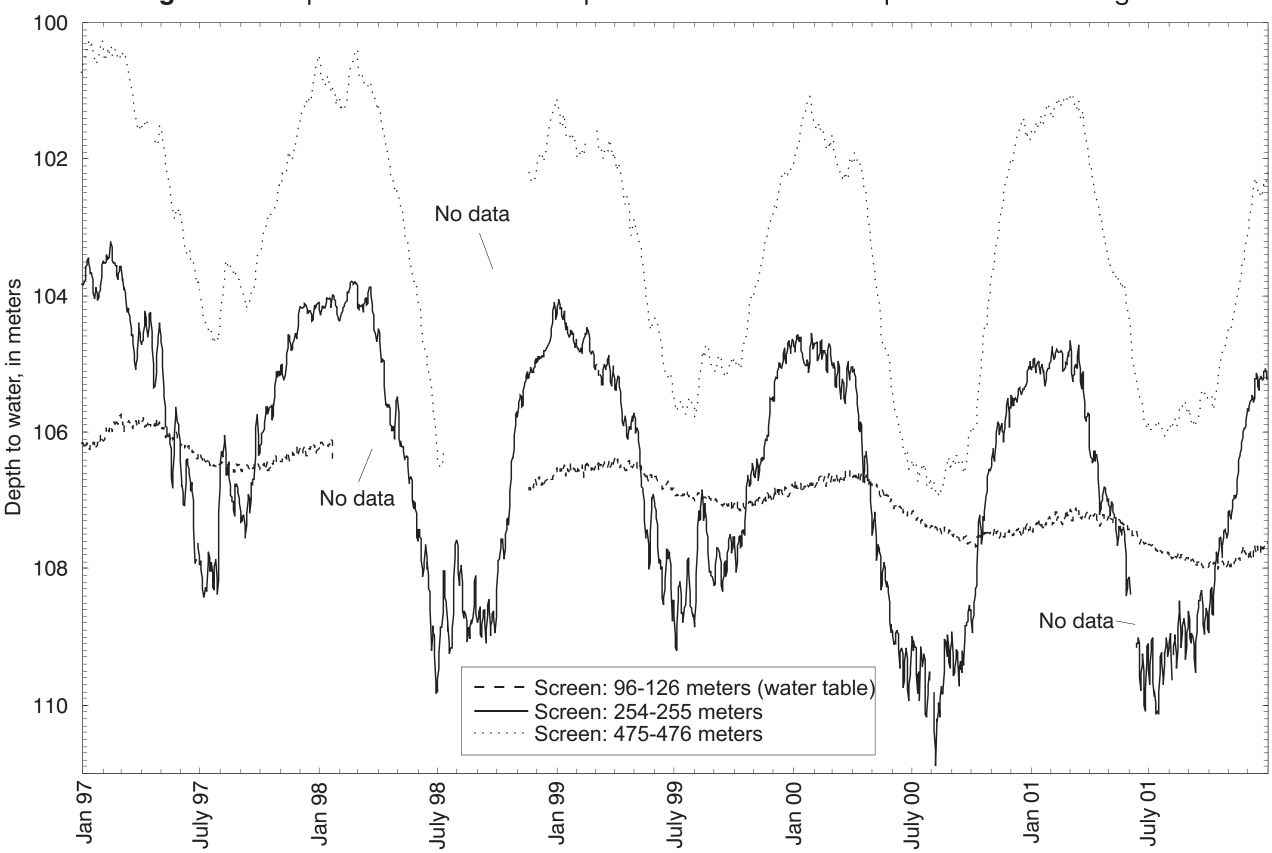


Figure 5B. Depth to water in Del Sol Divider piezometers. Location of piezometer site in figure 2D.

The subsequent 211-day (September 3, 1995, to April 1, 1996; fig. 2B) interferogram encompasses a period of seasonal water-level recovery. The reversed sense of deformation (that is, uplift in locations of subsidence features observed in the previous 793-day interferogram) is the elastic response of the aquifer system to recovering water levels.

The 1,004-day interferogram (fig. 2C; July 2, 1993, to April 1, 1996) encompasses 2 3/4 years of long-term water-level decline with an extra seasonal recovery period superimposed. Although subsidence and uplift features are observed in this interferogram, subsidence features predominate. Considering the summer to late-winter seasonal span by the interferogram and the widespread uplift observed in the 211-day (fig. 2B) interferogram (presumably during a period of water-level recovery), it is probable that permanent (inelastic) compaction and subsidence are accumulating over yearly or longer time scales. This is partly corroborated by the subsidence observed in the 793-day interferogram (fig. 2A). Because water-level data do not exist for these areas during the time spanned by these interferograms, it is not possible to determine conclusively whether the subsidence is recoverable (elastic) or permanent. In Rio Rancho, profile A-A' crosses the prominent quadrilateral-shaped feature, for which the magnitude of subsidence observed in the 793-day (fig. 2A) interferogram and subsequent elastic rebound observed in the 211-day (fig. 2B) interferogram are about 48 and 24 mm, respectively.

The 385-day interferogram (fig. 2D; February 10, 1997, to March 2, 1998) closely encompasses one cyclic period of seasonal water-level change. Minimal net water-level change was observed in the Garfield and Del Sol Divider piezometers (fig. 5A,5B) during this time, and insignificant land-surface elevation change is observed at these locations in the interferogram. The water level in the Sister Cities 1 piezometer (site location shown in fig. 2D) declined 1.74 m during this period; subsidence is observed in this area of north Albuquerque. Displacement features in Rio Rancho exhibit both subsidence and elastic rebound, presumably in response to net ground-water-level changes.

The 560-day interferogram (fig. 2E; March 2, 1998, to September 13, 1999) again encompasses a period with both long-term and seasonal water-level changes superimposed. Hydrographs for deeper piezometers at the Garfield and Del Sol Divider sites (fig. 5A,5B) indicate about 2 and 4 m, respectively, of net water-level decline during this period. Relatively small and uniform subsidence is observed in this area of the interferogram.

Geologic Structures in the Study Area that Influence Ground-Water Flow

The quadrilateral-shaped displacement feature observed in Rio Rancho in all five interferograms, and particularly the 211-day interferogram (fig. 2B), correlates with the location of the Zia Horst, a known fault-bounded, local structural uplift. This horst juxtaposes relatively permeable, well-sorted sand of the Zia Sand of Tertiary age against outlying, stratigraphically younger sediment. Greater diagenetic cementation (Sean Connell, New Mexico Bureau of Geology and Mineral Resources, oral commun., 2001) in the outlying sediment may have imparted a lower permeability and compressibility to this sediment; horst-bounding faults also appear to impede ground-water flow. Subsidence is observed over the Zia Horst in the 793-day interferogram (fig. 2A), presumably due to pumpage from a well near the west fault-bounded side of the structure. The subsequent 211-day interferogram (fig. 2B) shows elastic rebound over this structure as ground-water levels recovered. The light-blue subsidence lobes northwest and northeast of this block of relatively high permeability suggest that water levels declined in those areas during this 211-day period, though no significant ground-water withdrawals occurred. These water-level declines may be a response to drawdown in this area during the previous interferogram period, which was delayed by low permeability of the block-bounding faults. This interpretation suggests the possibility that the water-level response inferred from a continuous series of short temporal-baseline interferograms could be used to estimate the effective hydraulic conductivity of a fault "flow barrier" in an elastically deforming aquifer system.

On the east side of the interferograms, the Rincon and Sandia normal faults (fig. 2B) are basin-bounding structures that separate crystalline rock of Precambrian age to the east from basin-fill alluvium of Tertiary and Quaternary age (Kelly, 1977) to the west; the eastern limit of the observed InSAR-derived displacements in Albuquerque corresponds with this boundary. The Alameda, Eubank, and Coronado Faults are north-trending, west-dipping normal faults that make up the east heights fault zone. Offsets in deposits of Tertiary and Quaternary age observed in drill-hole lithologic and geophysical logs were used to map these faults. The boundaries of the displacement lobes observed in the 793- and 211-day interferograms (fig. 2A,2B) correlate well with the mapped extent of these faults, suggesting that the faults have low permeability, which impedes the propagation of water-level changes. As noted in the Ground-displacement observations section for the 793- and 211-day interferograms, these apparent subsidence and elastic-rebound lobes could be artifacts resulting from localized tropospheric delays in the September 3, 1995, SAR data.

An additional interferogram spanning a time with similar water-level variations would help discriminate between these alternatives. The 385-day (fig. 2D) interferogram does not span a time with significant seasonal water-level change. The 560-day (fig. 2E) interferogram spans such a seasonal change but was contaminated by atmospheric effects in the area of interest. SAR data from January to August 1997 were collected and span a time with seasonal water-level variation. An interferogram processed from these data may further illuminate the presence of permeability barriers in the Albuquerque and Rio Rancho areas.

The north-south trends of the northeast heights faults (fig. 2B) are from a compilation by Hudson and others (1999). Connell (2000) interpreted a northwesterly trend divergence of these faults in north Albuquerque, in accordance with a regional structural interpretation (John Hawley, oral commun., 2000). The northwesterly trend of the eastern boundary of the subsidence lobe in figure 2A may support this interpretation. Because water-level change (and consequent observed elastic compression) is a convolved response to pumping and spatially variable aquifer-system hydraulic diffusivities, it is difficult to discriminate the hydraulic effect of these structural alternatives without ground-water flow modeling.

Plummer and others (2001) mapped zones of different water quality in the Albuquerque area. Differences in stable isotopes discriminate zones containing ground water recharged from the Sandia Mountains or the Rio Grande. The boundary between two zones generally corresponds with the northeast heights fault zone location, further suggesting that ground-water flow from the mountain front is impeded by low-permeability faults, such as the Alameda, Eubank, and Coronado strands of the northeast heights fault zone.

CONCLUSIONS

Interferometric measurements of land-surface elevation change suggest that aquifer-system compression resulting from ground-water withdrawals in the Albuquerque area has probably remained elastic (recoverable) from July 1993 through September 1999. Evidence suggests that some inelastic (permanent) compaction and land subsidence may have occurred in the Rio Rancho area, but this cannot be concluded because of the absence of ground-water-level data for the same periods of the interferograms. Patterns of land subsidence and uplift in both Albuquerque and Rio Rancho suggest that intrabasin faults may impede ground-water diffusion at seasonal time scales. Alternatively, apparent patterns of compression and elastic rebound may result from spatially coincident tropospheric delay effects in the September 3, 1995, SAR data. An additional interferogram spanning the time from January to August 1997 may help discriminate between these alternatives.

SELECTED REFERENCES

Amelung, F., Galloway, D.L., Bell, J.W., Zebker, H.A., and Laczniak, R.J., 1999, Sensing the ups and downs of Las Vegas—InSAR reveals structural control of land subsidence and aquifer-system deformation: Geology, v. 27, p. 483-486.

Bartolino, J.R., and Cole, J.C., 2002, Ground-water resources of the Middle Rio Grande Basin, New Mexico: U.S. Geological Survey Circular 1222, 132 p.

Bawden, G.W., Thatcher, W., Stein, R.S., Hudnut, K.W., and Peltzer, G., 2001, Tectonic contraction across Los Angeles after removal of groundwater pumping effects: Nature, v. 412, p. 812-815.

Bell, J.W., 1981a, Results of leveling across fault scarps in Las Vegas Valley, Nevada, April 1978 - June 1981: Nevada Bureau of Mines and Geology Open-File Report 81-5, 7 p.

———1981b, Subsidence in Las Vegas Valley: Nevada Bureau of Mines and Geology Bulletin 95, 83 p., 1 pl.

Bell, J.W., and Price, J.G., 1993, Subsidence in Las Vegas Valley, 1980-91—Final project report: Nevada Bureau of Mines and Geology Open-File Report 93-4, 10 sections, 9 pls., variously paged.

Carpenter, M.C., 1993, Earth-fissure movements associated with fluctuations in ground-water levels near the

Picacho Mountains, south-central Arizona, 1980–84: U.S. Geological Survey Professional Paper 497-H, 49 p.

Carpenter, M.C., 1999, South-central Arizona—Earth fissures and subsidence complicate development of desert water resources, *in* Galloway, D.L., Jones, D.R., and Ingebritson, S.E., eds., Land subsidence in the United States: U.S. Geological Survey Circular 1182, p. 65-78.

Centre National d'Etudes Spatiales (C.N.E.S.), 1997, PRISME/DIAPASON Software: Toulouse, France, version 1.0.

Connell, S.D., 2000, Geology of the Alameda quadrangle, Bernalillo and Sandoval Counties, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources Open-File Map GM-10, 1 sheet, scale 1:24,000.

Fielding, E.J., Blom, R.G., and Goldstein, R.M., 1998, Rapid subsidence over oil fields measured by SAR interferometry: Geophysical Research Letters, v. 27, p. 3,215-3,218.

Gabriel, A.K., Goldstein, R.M., and Zebker, H.A., 1989, Mapping small elevation changes over large areas—Differential radar interferometry: Journal of Geophysical Research, v. 94, p. 9,183-9,191.

Galloway, D.L., Hudnut, K.W., Ingebritsen, S.E., Phillips, S.P., Peltzer, G., Rogez, F., and Rosen, P.A., 1998, Detection of aquifer system compaction and land subsidence using interferometric synthetic aperture radar, Antelope Valley, Mojave Desert, California: Water Resources Research, v. 34, p. 2,573-2,585.

Galloway, D.L., Jones, D.R., and Ingebritsen, S.E., eds., 1999, Land subsidence in the United States: U.S. Geological Survey Circular 1182, 175 p.

———2000, Measuring land subsidence from space: U.S. Geological Survey Fact Sheet 051-00, 4 p.

Goldstein, R.M., Zebker, H.A., and Werner, C.L., 1988, Satellite radar interferometry—Two-dimensional phase unwrapping: Radio Science, v. 23, no. 4, p. 713-720.

Hanssen, R.F., 2001, Radar interferometry: Boston, Kluwer Academic Publishers, 308 p.

Heywood, C.E., 1997, Piezometric-extensometric estimations of specific storage in the Albuquerque Basin, New Mexico, *in* Prince, K.R., and Leake, S.A., eds., U.S. Geological Survey Subsidence Interest Group Conference--Proceedings of the technical meeting, Las Vegas, Nevada, February 14-16, 1995: U.S. Geological Survey Open-File Report 97-47, p. 21-26.

———1998, Piezometric-extensometric estimations of specific storage in the Albuquerque Basin, New Mexico, *in* Borchers, J.W., ed., Land subsidence case studies and current research: Proceedings of the Dr. Joseph F. Poland Symposium on Land Subsidence, Association of Engineering Geologists Special Publication no. 8, p. 435-440.

Hoffmann, Jörn, Zebker, H.A., Galloway, D.L., and Amelung, F., 2001, Seasonal subsidence and rebound in Las Vegas Valley, Nevada, observed by synthetic aperture radar interferometry: Water Resources Research, v. 37, no. 6, p. 1,551-1,566.

Holzer, T.L., 1998, History of the aquitard-drainage model in land subsidence case studies and current research, *in* Borchers, J.W., ed., Land subsidence case studies and current research: Proceedings of the Dr. Joseph F. Poland Symposium on Land Subsidence, Association of Engineering Geologists Special Publication no. 8, p. 7–12.

Hudson, M.R., Minor, S.A., Grauch, V.J.S., and Personius, S.F., 1999, Preliminary characterization of faults in the Middle Rio Grande Basin, *in* Bartolino, J.R., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Third Annual Workshop, Albuquerque, New Mexico, February 24-25, 1999: U.S. Geological Survey Open-File Report 99-203, p. 40-41.

Ikehara, M.E., Galloway, D.L., Fielding, E.J., Bürgmann, R., Lewis, A.S., and Ahmadi, B., 1998, InSAR imagery reveals seasonal and longer-term land-surface elevation changes influenced by ground-water levels and fault alignment in Santa Clara Valley, California [abs.]: EOS (supplement) Transactions, American Geophysical Union, no. 45, November 10, 1998, p. F37.

Ikehara, M.E., and Phillips, S.P., 1994, Determination of land subsidence related to ground-water-level declines using global positioning system and leveling surveys in Antelope Valley, Los Angeles and Kern Counties, California, 1992: U.S. Geological Survey Water-Resources Investigations Report 94-4184, 101 p.

Ireland, R.L., Poland, J.F., and Riley, F.S., 1984, Land subsidence in the San Joaquin Valley, California, as of 1980: U.S. Geological Survey Professional Paper 437-I, 93 p.

Kelly, V.C., 1977, Geology of the Albuquerque basin, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources Memoir 33, 60 p.

Laney, R.L., Raymond, R.H., and Winikka, C.C., 1978, Maps showing water-level declines, land subsidence, and earth fissures in south-central Arizona: U.S. Geological Survey Water-Resources Investigations Report 78-83, 2 sheets, scale 1:125,000.

Machette, M.N., Personius, S.F., Kelson, K.I., Haller, K.M., and Dart, R.L., 1998, Map and data for Quaternary faults in New Mexico: U.S. Geological Survey Open-File Report 98-521, 443 p., 1 pl., scale 1:750,000.

Massonnet, D., Briole, P., and Arnaud, A., 1995, Deflation of Mount Etna monitored by spaceborne radar interferometry: Nature, v. 375, p. 567-570.

Massonnet, D., and Feigl, K.L., 1998, Radar interferometry and its application to changes in the Earth's surface: Reviews of Geophysics, v. 36, p. 441-500.

Massonnet, D., Feigl, K.L., Rossi, M., and Adragna, F., 1994, Radar interferometric mapping of deformation in the year after the Landers earthquake: Nature, v. 369, p. 227-230.

Massonnet, D., Holzer, T.L., and Vadon, H., 1997, Land subsidence caused by the East Mesa geothermal field, California, observed using SAR interferometry: Geophysical Research Letters, v. 24, p. 901-904.

Massonnet, D., Rossi, M., Carmona, C., Adragna, F., Peltzer, G., Feigl, K.L., and Rabaute, T., 1993, The displacement field of the Landers earthquake mapped by radar interferometry: Nature, v. 364, p. 138-142.

Moore, S.J., and Anderholm, S.K., 2001, Ground-water monitoring in the Middle Rio Grande Basin, central New Mexico—Implications of water-level variations in nested piezometers [abs.]: Geological Society of America, 2001 Abstracts with Programs, Rocky Mountain and South-Central Sections, v. 33, no. 5, p. A-54.

National Research Council, 1991, Mitigating losses from land subsidence in the United States: Washington, D.C., National Academy Press, 58 p.

Peltzer, G., Crampe, F., and King, G., 1999, The Mw7.6, Manyi (Tibet) earthquake—Surface rupture, surface displacement field, and fault slip solution from ERS SAR data: EOS, Transactions of the American Geophysical Union, v. 80, no. 46, p. 1,023.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., and Busenberg, Eurybiades, 2001, Geochemical characterization of ground-water flow in parts of the Santa Fe Group aquifer system, Middle Rio Grande Basin, New Mexico, *in* Cole, J.C., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico, February 15-16, 2000: U.S. Geological Survey Open-File Report 00-488, p. 7-10.

Poland, J.F., ed., 1984, Guidebook to studies of land subsidence due to ground-water withdrawal: Paris, United Nations Educational, Scientific and Cultural Organization, Studies and reports in hydrology 40, 305 p.

Poland, J.F., and Ireland, R.L., 1988, Land subsidence in the Santa Clara Valley, California, as of 1982: U.S. Geological Survey Professional Paper 497-F, 61 p.

Poland, J.F., Lofgren, B.E., Ireland, R.L., and Pugh, R.G., 1975, Land subsidence in the San Joaquin Valley, California, as of 1972: U.S. Geological Survey Professional Paper 437-H, 78 p.

Rosen, P.A., Hensley, S., Zebker, H.A., Webb, F.H., and Fielding, E.J., 1996, Surface deformation and coherence measurements of Kilauea volcano, Hawaii, from SIR-C radar interferometry: Journal of Geophysical Research, v. 101, p. 23, 109-23, 125.

Shindle, M., 1999, ESCHER—An algorithm for unwrapping an interferogram phase file using the branch-cut method: Fairbanks, Alaska SAR Facility.

Sneed, Michelle, and Galloway, D.L., 2000, Aquifer-system compaction and land subsidence—Measurements, analyses, and simulations—the Holly site, Edwards Air Force Base, Antelope Valley, California: U.S. Geological Survey Water-Resources Investigations Report 00-4015, 65 p.

Sneed, Michelle, Ikehara, M.E., Galloway, D.L., and Amelung, F., 2001, Detection and measurement of land subsidence using global positioning system and interferometric synthetic aperture radar, Coachella Valley, California: U.S. Geological Survey Water-Resources Investigations Report 01-4193, 26 p.

Terzaghi, Karl, 1925, Erdbaumechanik auf Bodenphysikalischer Grundlage: Wein Leipzig, Deuticke, 399 p.

Vadon, H., and Sigmundsson, F., 1997, 1992-1995 crustal deformation at Mid-Atlantic ridge, SW Iceland, mapped by radar interferometry: Science, v. 275, p. 193-197.

Wicks, C., Jr., Thatcher, W., and Dzurisin, D., 1998, Migration of fluids beneath Yellowstone Caldera inferred from satellite radar interferometry: Science, v. 282, p. 458-462.

Zebker, H.A., Rosen, P.A., Goldstein, R.M., Gabriel, A.K., and Werner, C.L., 1994, On the derivation of coseismic displacement fields, using differential radar interferometry—The Landers earthquake: Journal of Geophysical Research, v. 99, p. 19,617-19,634.

U.S. Department of the Interior
U.S. Geological Survey, WRD
5338 Montgomery Blvd. NE, Suite 400
Albuquerque, NM 87109-1311

BOOK RATE

Printed on recycled paper

C.E. Heywood, D.L. Galloway, and S.V. Stork—GROUND DISPLACEMENTS CAUSED BY AQUIFER-SYSTEM WATER-LEVEL VARIATIONS OBSERVED USING INTERFEROMETRIC SYNTHETIC APERTURE RADAR NEAR ALBUQUERQUE, NEW MEXICO—U.S. Geological Survey Water-Resources Investigations Report 02-4235