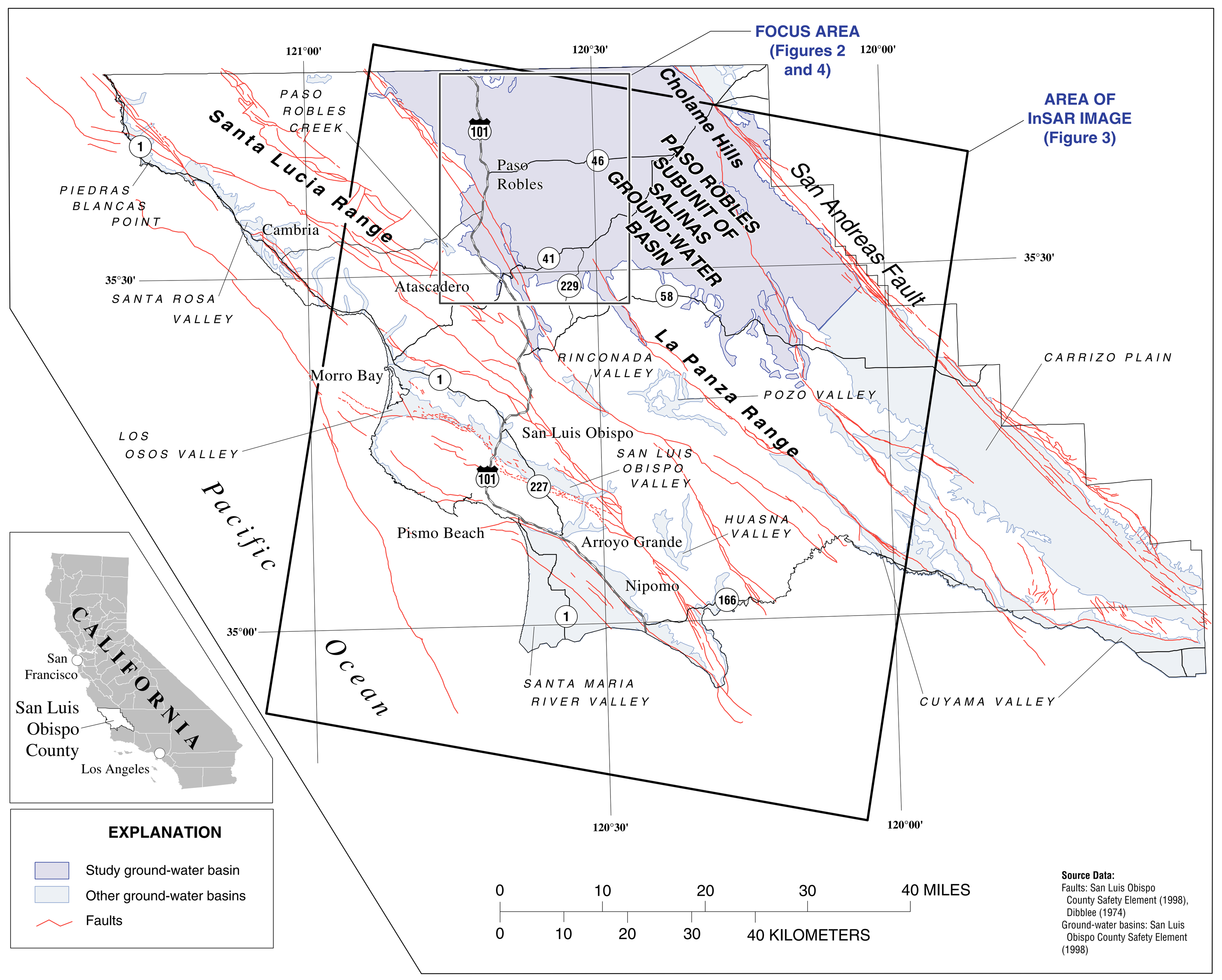

Figure 1. Map of focus area, ground-water basins, physical and cultural features of San Luis Obispo County and area of InSAR coverage.

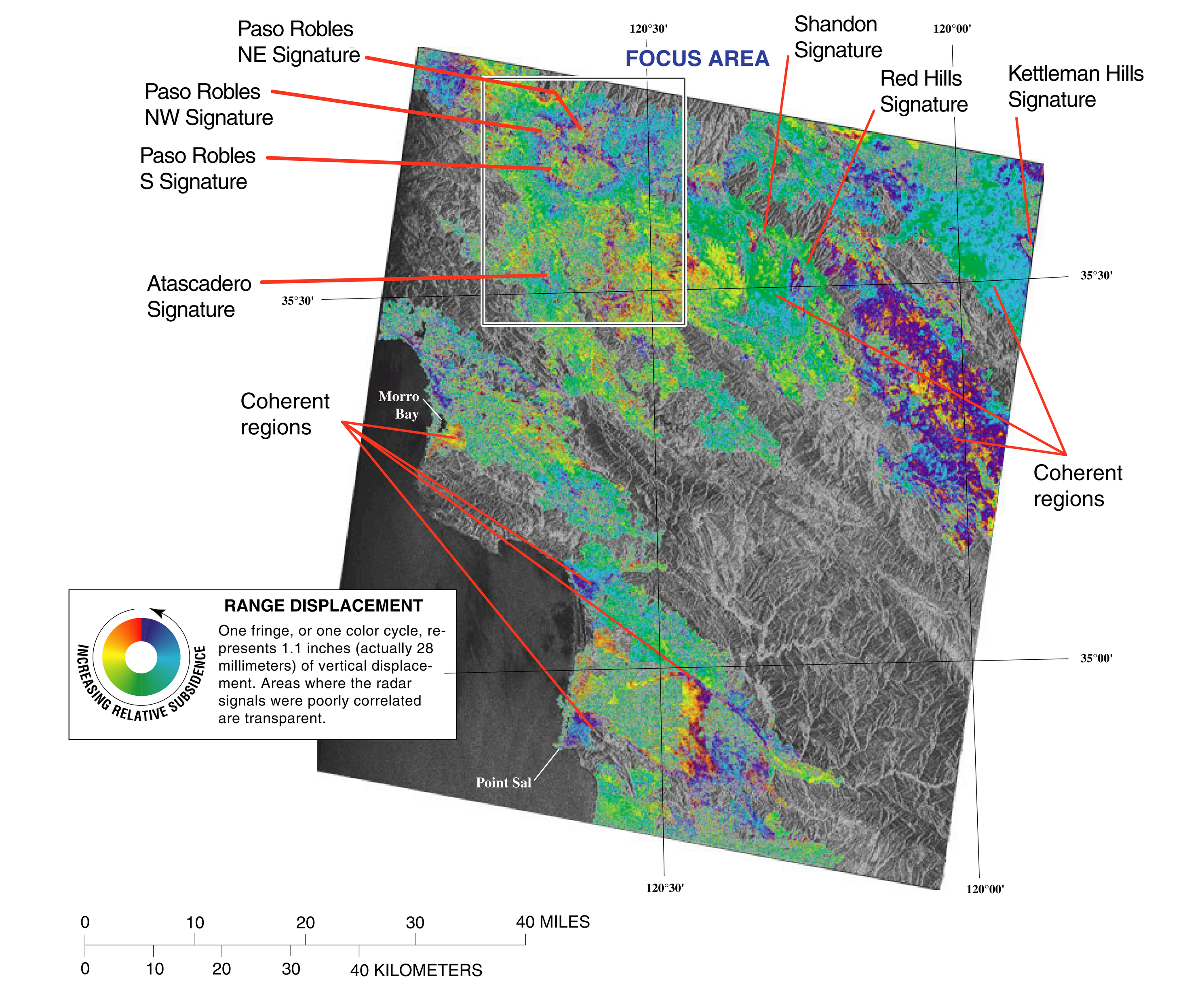

Figure 3. InSAR imagery of full scene covering most of San Luis Obispo County with focus area outlined (area outlined on figure 1).

Introduction

During the 1990's, the population of San Luis Obispo County has grown steadily, and some land use has been converted from dry farming and grazing to irrigated vineyards and urban areas. Because surface-water supplies are insufficient to meet the growing demand for water, ground-water pumpage has increased and the resulting water-level declines have raised concern that this water resource may become overstressed. To address this concern many questions need to be answered. One particular concern is whether the larger ground-water basins within the county function as large individual basins or whether subsurface structures divide these large basins into smaller subbasins, as differences in ground-water-level data suggest. In 1999, the San Luis Obispo County Flood Control and Water Conservation District entered into a cooperative agreement with the U.S. Geological Survey to test the validity of using Interferometric Synthetic Aperture Radar (InSAR) as a tool to aid in locating subsurface structures in ground-water basins by determining seasonal and historical land-surface changes.

Spaceborne InSAR has been used to identify displacements of the land surface caused by aquifer-system compaction in other ground-water basins, such as the basins in Antelope Valley, California (Galloway and others, 1998); Santa Clara Valley, California (Ikehara and others, 1998); and in the Las Vegas area of Nevada (Amelung and others, 1999). Spatially detailed InSAR imagery of these basins show that InSAR can reveal sub-centimeter vertical land-surface displacements. Owing to the high spatial detail of InSAR imagery, the InSAR-derived displacement maps can be used with ground-water-level data to reveal differential aquifer-system compaction related to the presence of geological structures or the distribution of compressible sediments that may define subbasin boundaries. Many faults have already been identified in San Luis Obispo County, but identifying additional faults or other hydrologic barriers hidden in the subsurface is important to understanding ground-water flow. InSAR displacement maps of the Paso Robles area of San Luis Obispo County were compared with maps of seasonal changes in ground-water levels to detect the presence of aquifer-system compaction. Other areas of potential aquifer-system compaction within the county also were identified but are not discussed in detail here.

Location and Description of Study Area

The area of the study includes most of San Luis Obispo County, California, which is located about 160 miles northeast of Los Angeles, California (Figure 1). The climate of the area is characterized by dry summers and relatively wet winters with most of the 13 inches of mean annual precipitation occurring during the winter (Paso Robles Information Services, www page, Internet URL <http://www.pasorobleschamber.com/facts/index.htm>). The primary focus of this study is a 400-square-mile area near Paso Robles, which includes part of the Paso Robles subunit of the Salinas ground-water basin (Figure 1). This area has been proposed for a more intense study and would benefit from better definition of the extent and continuity of the ground-water basin.

The Paso Robles subunit is bounded by the Cholame Hills on the northeast, the Santa Lucia Range on the southwest and west, and the La Panza Range on the south. The main water-bearing units in the Paso Robles subunit are Quaternary younger and older alluvium and Quaternary and Tertiary continental sediments of the Paso Robles Formation (Figure 2). The younger and older alluvium consists of poorly sorted, unconsolidated gravel, sand, and silt. The Paso Robles Formation consists of unconsolidated to poorly consolidated coarse sand and gravel, as well as finer sand, silt, and clay and some limestone that formed from deposition in floodplains and small lakes. The water-bearing units are underlain by non-water-bearing Tertiary and Cretaceous bedrock and granite. Mapped faults crossing the basin include the San Marcos, Rinconada, and La Panza faults (Campion and others, 1983).

Methodology

InSAR

InSAR is a means for remotely mapping land-surface displacements. Paired, synthetic-aperture radar (SAR) images taken from earth-orbiting satellites are used to create an interference image or interferogram. The interferogram shows the change in the radar line-of-sight distance, or range, between land surface and the radar antenna between the paired images. The interferogram can be viewed as a spatially detailed displacement map with 1,600-6,400 square meter pixels generally attainable. For a particular pixel, a resolution of range displacement is on the order of hundredths of an inch (millimeters). In coherent radar echoes, the phase is exactly proportional to the measured time delay and effective path length of the signal. The path differences of two signals can be determined by observing the phase differences or signature of the echoes. This phase signature is represented graphically by a color fringe. Range displacements are identified from coherent phase signatures between the two radar scenes on the interferogram. For C-band radar of the European Remote Sensing (ERS) platforms, the maximum detectable phase shift is one-half the wavelength of the radar microwave, which represents 1.1 inches (28 millimeters) of range displacement. Larger range displacements are calculated by identifying multiple coherent phase signatures from color fringes on the image; 1.1 inches (28 millimeters) of range displacement for each color fringe plus some fraction of 1.1 inches (28 millimeters) for a partial color fringe. Thus, the interferogram represents a displacement map of phase signatures in the range of 0-1.1 inches (0-28 millimeters), but range displacements exceeding 1.1 inches (28 millimeters) can be calculated by counting color fringes on the imagery. Because the line-of-sight of the ERS satellites are reclined 23 degrees from vertical at the center of the radar image, an equivalent vertical displacement represented by one color fringe on an interferogram would be slightly larger than the range displacement, about 1.2 inches (30.5 millimeters).

The resulting map of phase signatures can be related to several factors; displacement of the land surface, topographic effects, and changes in the travel time of the radar signal owing to tropospheric delays. Topographic effects were removed using a 1-day tandem interferogram (Zebker and others, 1994b) processed from SAR scenes imaged on succeeding days. Subtraction of the tandem interferogram from the original interferogram results in the "change" interferogram that contains range displacements from ground displacements plus any tropospheric delays.

For this study, raw SAR images made by European Remote Sensing satellites ERS-1 and ERS-2 were used. Five-month, 7-month, 15-month, and 20-month interferograms were created using techniques described by Zebker and others (1994a), Peltzer and Rosen (1995), Peltzer and others (1996), and Galloway and others (1998). Each of the four interferograms (3861 square miles or 10,000 square kilometers) was examined for coherent phase signatures. Only the 5-month interferogram (Figures 3 and 4) from March 28 to August 15, 1997, showed coherent phase signatures that warranted further examination. Topographic effects were removed using a 1-day tandem interferogram processed from SAR scenes imaged on December 29 and 30, 1995. The lack of coherent phase signatures in the 7-, 15-, and 20-month interferograms is due to atmospheric effects on the radar signal or temporal decorrelation of the interferograms. Areas where it was not possible to correct for tandem effects are excluded from the differential interferograms, and instead, the gray-scale image of the radar amplitude is shown.

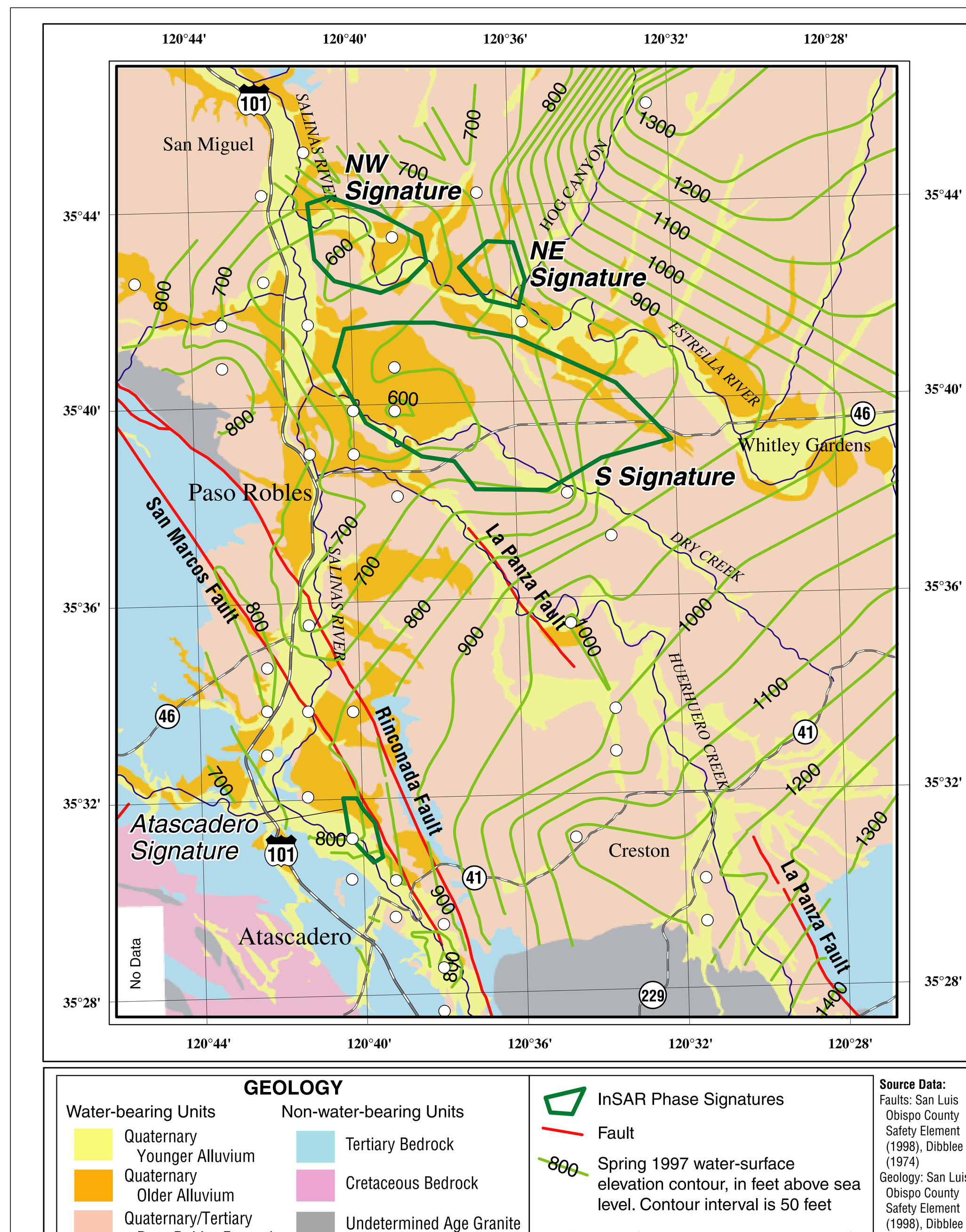

Figure 2. Generalized geologic map of the Paso Robles area with water-surface elevation contours for spring 1997.

Ground-Water Levels

Water-level data for 58 wells for both the spring and fall of 1997 in 40 public land survey sections were obtained from San Luis Obispo County Flood Control and Water Conservation District (unpublished data, 1999). Although the state well number was provided for the wells, the exact well locations are not known. Therefore, all wells in a section were assigned an approximate position that corresponds with the center of the section, and thus well locations may be off by as much as 0.7 mile. Because the data are sparse, a triangular-irregular mesh was used to construct the contour maps of spring 1997 water-surface elevations (Figure 2) and the seasonal ground-water level change (Figure 4). The seasonal ground-water level change was calculated by subtracting fall 1997 water levels from spring 1997 water levels.

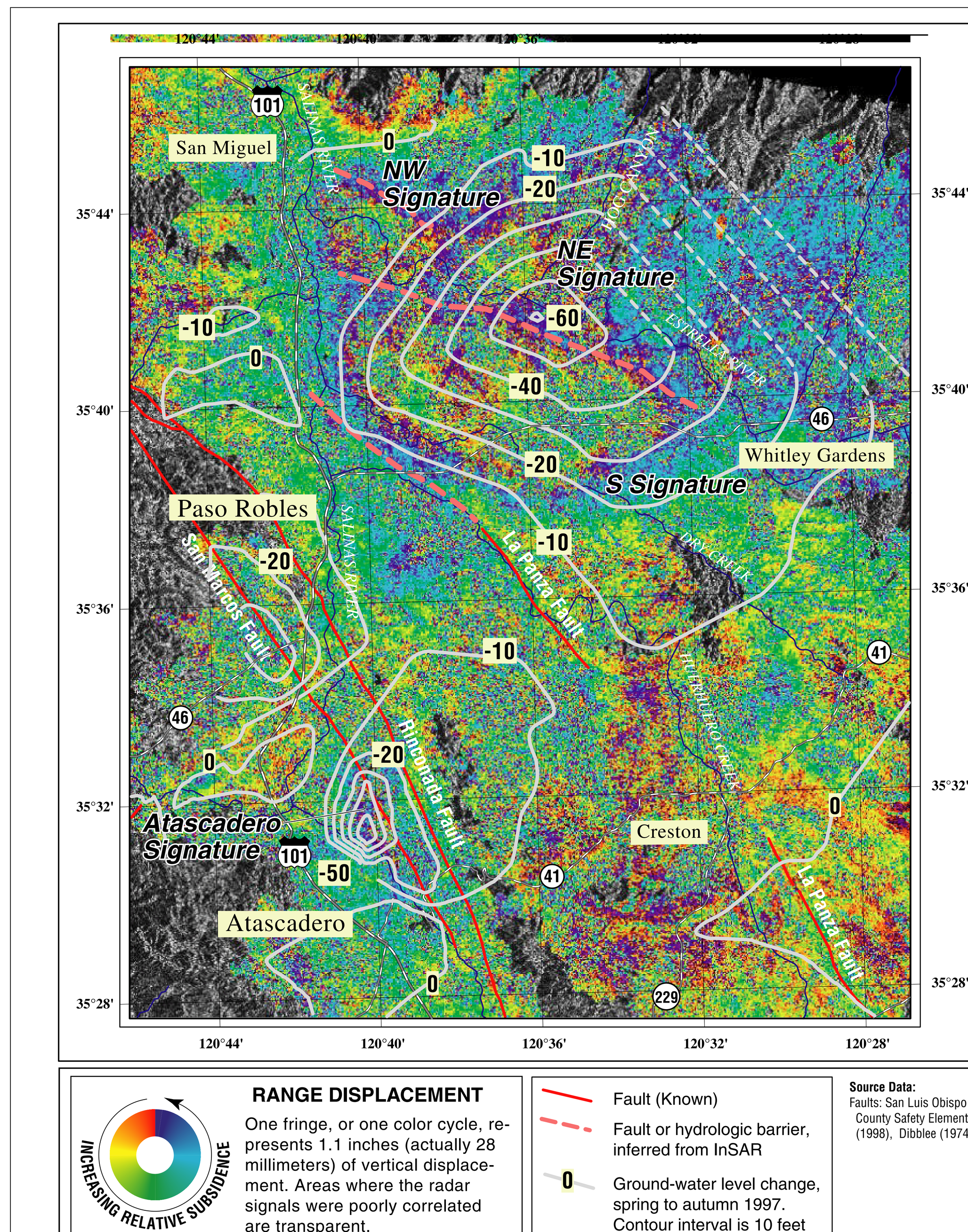

Figure 4. InSAR image of the Paso Robles area and seasonal ground-water level change for spring to autumn 1997.

Results

The interferogram for March 28-August 15, 1997, shows four phase signatures in two separate locations within the area of primary focus for this study (Figure 4). Three of these signatures are located northeast of Paso Robles and the other is northeast of Atascadero (Figure 4). Other coherent phase signals, outside of the area of primary focus, are also apparent on this interferogram.

Paso Robles

The interferogram shows three phase signatures about 3 miles northeast of Paso Robles (Figure 4). These three phase signatures lie along the trend of an unmapped syncline with the thicknesses of Paso Robles formation sediments exceeding 4,000 feet (Dibblee, USGS, oral commun., 1999). The southern signature shows a relative change of about two phase signatures (2.1 inches or 56 millimeters) of increasing range distance (downward land-surface displacement) in an approximately 75-square-mile area. The maximum downward displacement in the northwest signature is about 0.8 inches (20 millimeters) and the northeast signature is 0.6 inches (about 14 millimeters). The southern and northeastern phase signatures coincide with an area of seasonal water-level decline of about 60 feet (Figure 4); downward displacement in these areas may be related to water-level declines. The northwestern phase signature also appears to coincide with a depression in the spring 1997 water-surface elevation (Figure 2). The southwestern boundary of the southern phase signature is subparallel to an extension of the La Panza Fault (Dibblee, 1974) and appears to be bounded by the fault. The northwestern and northeastern phase signatures do not appear to be related to any mapped geological structures, but their separation from the southern phase signature may suggest the presence of a ground-water boundary or barrier (Figure 4). The separation of the northeast and northwest phase signatures appear to coincide with the northeast trending ground-water contours (just north of Hog Canyon in Figure 2), which may indicate the presence of a ground-water boundary or barrier. It is also possible that the concentration of pumping in the areas of these three phase signatures and the subsequent water-level declines has caused localized ground-surface displacement and that these are not barriers or subbasin boundaries.

Atascadero area

The interferogram (Figure 4) shows an areally small phase signature in the Atascadero area east of Highway 101 and the Salinas River. The eastern edge of the signature is bordered by the San Marcos and the Rinconada faults. The phase signature appears to be controlled, in part, by the ground-water barriers formed by the faults and by the geometry of the basins adjacent to the faults. The phase signature shows about 1 to 2 inches (28 to 56 millimeters) of downward ground displacement, which coincides with the seasonal water-level declines between spring and fall 1997 of about 54 feet (Figure 4).

Other regions

In addition to the phase signatures identified in the area of primary focus, coherent regions also were identified in seven additional regions of the interferogram (Figure 3). In the Kettleman Hills area, as much as 4 inches (110 millimeters) of land-surface displacement was identified in two oil fields using InSAR (Fielding and others, 1998). This displacement probably is related to withdrawal of oil from the area and not to the withdrawal of ground water. In the Shandon and Red Hills areas, as much 2 inches (56 millimeters) of displacement was identified, which is apparently related to pumping for agricultural use. Coherent phase signals also were identified in the Morro Bay, Arroyo Grande/Pismo Beach/Nipomo, Santa Maria Valley area, and Point Sal areas.

Summary and Conclusions

During the 1990's, the population of San Luis Obispo County has grown steadily and surface-water supplies have been insufficient to meet the growing demand for water. Ground-water pumpage has increased to meet this shortfall, resulting in seasonal water-level declines and concern that the water resources of the area may become overstressed. One particular concern is whether the larger ground-water basins within the county function as large individual basins or whether subsurface structures divide these large basins into smaller subbasins. Interferometric Synthetic Aperture Radar was tested for use as a tool to aid in locating subsurface structures in ground-water basins by determining land-surface changes. Owing to the high spatial detail of InSAR imagery, the InSAR-derived displacement maps can be used with ground-water-level data to reveal differential aquifer-system compaction related to the presence of geological structures or the distribution of compressible sediment that may define subbasins.

The area of this study includes most of San Luis Obispo County, California, which is located about 160 miles northwest of Los Angeles, California. The primary focus of this study is a 400-square-mile area near Paso Robles. This area was selected for more intense investigation because a ground-water study for the area has been proposed that would benefit from better definition of the extent and continuity of the ground-water basins. The main water-bearing units in the Paso Robles area are Quaternary younger and older alluvium and Quaternary/Tertiary continental sediments.

InSAR is a means of remotely mapping land-surface displacements using paired synthetic-aperture radar images taken from earth-orbiting satellites. These images are used to create an interferogram that shows the change in the range between the land surface and the radar antenna on the order of millimeters for the paired images. The differences between two signals can be determined by observing the phase signatures of the radar echoes. These differences are represented graphically by a color fringe, which represents about 1.1 inches (28 millimeters) of range displacement. For this study, raw SAR images taken on March 28 and August 15, 1997, were used to create an interferogram. Water levels from 58 wells with both spring and fall 1997 measurements were used to construct water-level contour map for spring of 1997 and a seasonal water-level-change map for spring to fall 1997.

The interferogram showed three phase signatures about 3 miles northeast of Paso Robles, which indicated ground-surface displacements of from 0.6 to 2.1 inches (14 to 58 millimeters); the southern and northeast phase signatures coincide with an area of water-level decline of over 60 feet. There appears to be a ground-water barrier between the southern signature and the northeast and northwest signatures and also between the northeast and northwest signatures. These may not be actual barriers but more related to concentrated ground-water pumpage in the area of these signatures. The interferogram also shows an areally small phase signature in the Atascadero area that is bounded on the east by previously mapped faults and coincides with an area of seasonal ground-water level change of about 54 feet. The ground deformation in this area is on the order of 1 to 2 inches. In addition to those phase signatures in the area of primary focus, seven additional coherent phase signals were identified in other areas covered by the interferogram; Kettleman Hills, Shandon, Red Hills, Morro Bay, Arroyo Grande/Pismo Beach/Nipomo, Santa Maria Valley area, and Point Sal.

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Use of InSAR to Identify Land-Surface Displacements Caused by Aquifer-System Compaction in the Paso Robles Area, San Luis Obispo County, California, March to August 1997

David W. Valentine, Jill N. Densmore, Devin L. Galloway, and Falk Amelung, 2001

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