Final Technical Report

Award No. 06HQGR0037

INSAR ACROSS THE SIERRA NEVADA-BASIN AND RANGE TRANSITION ZONE

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Abstract

This study utilized interferometric synthetic aperture radar (InSAR) to search for contemporary crustal deformation within the Sierra Nevada-Basin and Range Transition Zone at the latitude of Reno, Nevada. In total, more than 110 interferometric pairs were processed. A systematic search of ERS-1, ERS-2, and Envisat radar data covering the 1992-2007 period was conducted in an effort to detect any ground deformation signals associated with multiple M >4.5 earthquakes occurring in the region. In particular, InSAR analysis was focused on a series of events occurring in the North Lake Tahoe area in 1998, 2003, and 2005 which were possibly associated with deep magma intrusion. The analyses further included a search for post-seismic deformation associated with the M 5.9 Double Spring Flat event, including several earthquakes in the M 4.5-5.0 range. We also looked for InSAR evidence of movement across several high strain-rate faults in the western Nevada region, including the fault segments of the Northern Walker Lane. The study also included InSAR mapping of groundwater and geothermal fluid extraction deformation signals in the alluvial basins of the region, since such signals can interfere with the geodetic strain measurements of nearby GPS stations.

The principal findings of the study showed that of 11 earthquakes of M >4.5 occurring since 1992, we could identify InSAR signals with only two sequences, the 1994 Double Spring Flat (M 5.9) and 2004 Adobe Hills (M 5.0-5.6) events. We could find no visible evidence of the 1998 (M 4.9) and 2005 (M 4.8) North Lake Tahoe events, eliminating the one visible InSAR signal as being related to groundwater pumping. We found numerous groundwater signals in many of the basins; these signals are strongly controlled by, and occur along, Quaternary faults. Most of the groundwater signals are seasonal in nature exhibiting alternating cycles of elastic subsidence and uplift. These observations together with wavelength filtering of radar phase data allowed us to segregate the seasonal signals and determine that the ground deformation along the faults was not tectonic.

Purpose of Study

This study utilized interferometric synthetic aperture radar (InSAR) to search for contemporary crustal deformation through the Sierra Nevada-Basin and Range transition zone and the northern Walker Lane, a region of elevated geodetic (GPS) displacement velocities (Hammond and Thatcher, 2004). In particular, we were looking for co-seismic and/or post-seismic ground deformation associated with medium-magnitude (M >4.5) earthquakes occurring in the region since 1992. Previous InSAR studies (Amelung and Bell, 2003) showed that the 1994 Double Spring Flat earthquake (M 5.9) had a distinct InSAR ground deformation pattern that allowed detailed modeling of the event and resolution of the fault motion. Since little to no surface fault rupture is generally associated with M 4.5-5.0 events, InSAR could potentially provide insights into relative surface motion if detectable signals were found for these events. Of particular interest was a sequence of events occurring north of Lake Tahoe, which included swarm activity in 2003 believed to be related to deep magma injection (Smith *et al.*, 2004).

In addition to searching for InSAR-observed deformation associated with tectonic events, this study looked for ground deformation signals associated with groundwater pumping and geothermal fluid extraction. Heavy groundwater pumping for municipal and agricultural use can produce significant seasonal and long-term response within the aquifer systems in the arid basins of Nevada (cf., Bell *et al.*, 2008), and such ground motion can potentially contaminate the geodetic strain rates of GPS stations located near such signals (Bawden *et al.*, 2001). Some continuous stations situated in bedrock in the Nevada region have been found to record anomalous motion due to heavy groundwater pumping (Gourmelen *et al*., 2007).

Approach

We processed a total of 110 InSAR pairs for a ~200 km x 200 km area of western Nevada between 1992-2007 (Fig. 1). This area is covered by radar acquired in four frames from the ERS-1, ERS-2, and Envisat satellites: Tracks 27 and 256, frames 2799 and 2817. Individual processed pairs and corresponding dates for each frame are listed in Tables 1-4. In addition, we processed radar data covering the 2004 Adobe Hills earthquake sequence. Radar scenes were obtained at no cost for this study from a European Space Agency Category-1 Data Grant to JW Bell, and from the archives of the WInSAR consortium. The InSAR processing was conducted primarily in the Nevada Bureau of Mines and Geology InSAR Laboratory operated by the Principal Investigator, with the assistance of Kurt Katzenstein, Graduate Research Assistant.

The InSAR Laboratory utilizes three processing software packages: Roi_Pac (developed by JPL); Gamma (developed by Gamma Remote Sensing); and Diapason (developed by the French Space Agency CNES). Additional Roi_Pac processing was conducted in the lab facilities of Co-Principal Investigator Gary Oppliger. Radar pairs were selected according to time period covered and geometrical baseline separations. Each processed pair produced radar phase-change interferograms in wrapped (repeating 2.8 cm phase-change fringes) and in unwrapped (total ground displacement) formats. Topographic

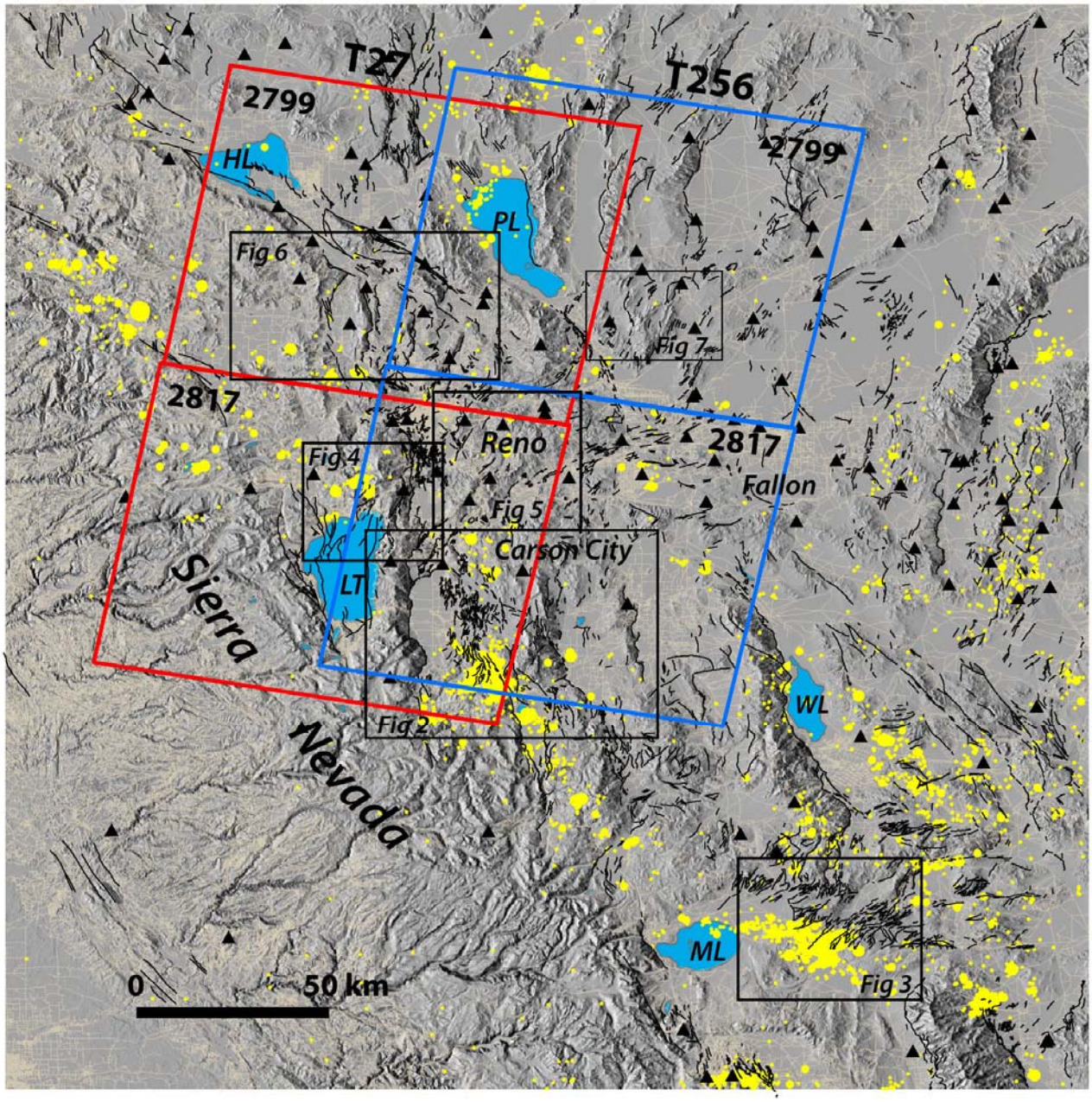


Figure 1. Sierra Nevada-Basin and Range Transition Zone covered by this study. InSAR pairs were processed for radar acquisitions in Frames 2799-2817 in Tracks 27 and 256. Selected interferograms shown in the following figures 2-7 are outlined by black boxes; earthquakes of M 2-5 for the period 1992-2007 are shown by yellow dots; existing geodetic GPS stations are shown by black triangles; Quaternary faults are shown by black lines (USGS Fault and Fold Database). Principal lakes: HL, Honey Lake; PL, Pyramid Lake; LT, Lake Tahoe; WL, Walker Lake; ML, Mono Lake.

phase contributions were removed from each interferogram using a 60m DEM created from the USGS National Elevation Data. Each interferogram was examined for evidence of phase-change signals. Detected signals were compared to locations of recorded earthquakes, groundwater-pumping, and geothermal extraction sites.

Table 1. Interferometric pairs processed for Track 27 Frame 2799; scene dates for pairs are in YYMMDD, and perpendicular baseline for the each pair is in meters.

Track 27 Frame 2799		
ERS		
Scene 1 date	Scene 2 date	B_p (m)
920503	930627	3
920503	950829	57
920503	960814	112
920503	000405	72
920503	010912	63
930627	950829	54
930627	970312	225
930627	010912	66
930905	951108	93
930905	970312	258
930905	980506	129
930905	020724	56
950829	000405	15
950829	010912	120
951108	970312	155
951108	980506	222
951108	000927	22
951108	020724	37
960814	000405	50
960814	010912	178
970312	000927	133
970312	020724	192
980506	000927	244
980506	020706	185
000405	010912	135
000927	020724	59
Envisat		
040623	050223	98
040901	051026	10
041006	050921	89
041110	050330	194
050608	051130	133

Table 2. Interferometric pairs processed for Track 27 Frame 2817; scene dates for pairs are in YYMMDD, and perpendicular baseline for the each pair is in meters.

Track 27 Frame 2817		
ERS		
Scene 1 date	Scene 2 date	B_p (m)
920503	930627	3
920503	950829	57
920503	960814	112
920503	000405	72
920503	010912	63
930627	950829	54
930627	960814	109
930627	970312	225
930627	000405	72
930627	010912	66
930905	951108	93
930905	980506	129
930905	970312	258
950829	960814	55
950829	010912	120
951108	970312	155
951108	980506	222
951108	000927	22
959829	000405	15
960814	000405	40
970312	000927	133
980506	000927	244
970312	010912	159
000405	010912	135
Envisat		
030430	060802	486
040623	041006	318
040623	041110	412
040623	060805	185
040623	051130	52
040901	050405	196
040901	051026	10
041006	050921	98
041110	050330	194
050405	050713	156
050405	051026	186
050405	060628	18
050608	051130	133
050608	061110	5
060508	070404	3
060524	061110	64
061110	070404	2

Table 3. Interferometric pairs processed for Track 256 Frame 2799; scene dates for pairs are in YYMMDD, and perpendicular baseline for the each pair is in meters.

Track 256 Frame 2799		
ERS		
Scene 1 date	Scene 2 date	B_p (m)
920414	931130	240
920414	951019	142
920414	951020	22
920414	000421	93
930817	970221	3
930817	970606	8
930817	020913	36
931130	951019	98
931130	951020	262
951020	000421	115
970221	970606	5
979696	020913	27
000804	020531	85

Table 4. Interferometric pairs processed for Track 27 Frame 2817 scene dates for pairs are in YYMMDD, and perpendicular baseline for the each pair is in meters.

Track 256 Frame 2817		
ERS		
Scene 1 date	Scene 2 date	B_p (m)
920414	931130	240
920414	951019	142
920414	951020	22
920414	000421	93
921110	930330	274
921110	960411	104
921110	970328	26
921110	990924	256
930330	931130	245
930330	951228	77
930330	960411	178
930817	970221	3
930817	970606	8
930817	020913	36
931130	951019	98
931130	951228	186
951019	951228	284
951019	951020	164
951019	000421	49
951020	000421	115
951228	960411	255
951228	990924	95
970221	970606	5
970221	020913	33
970328	990924	13

Table 5. List of earthquakes with M >4.5 that were examined in this InSAR study for evidence of ground deformation.

Date	Magnitude	Location
2 10 1993	4.6	N. of Pyramid Lake
9 12 1994	5.9	Double Spring Flat
11 15 1995	4.6	Cold Springs Valley
12 22 1995	4.9	Double Spring Flat
12 23 1995	5.0	Double Spring Flat
12 28 1995	4.9	Double Spring Flat
10 30 1998	4.9	North Tahoe
9 18 2004	5.4	Adobe Hills
9 18 2004	5.6	Adobe Hills
9 20 2004	5.0	Adobe Hills
6 26 2005	4.8	North Tahoe

InSAR Results

Tectonic signals

A comprehensive search of all pairs covering earthquakes with M >4.5 (Table 5) was made, and the only detected InSAR deformation signals were found to be associated with events of M >5.0 in the Double Spring Flat and Adobe Hills areas. Part of the study was focused in the North Lake Tahoe area, the site of two M 4.8-4.9 earthquakes believed to be possibly associated with deep magma injection.

Double Spring Flat

The 1994 Double Spring Flat earthquake (M 5.9) produced more than 10 cm of vertical ground deformation clearly delineated by a tear-dropped-shaped InSAR fringe pattern (Fig. 2); these InSAR data and the associated tectonic models are discussed in detail in Amelung and Bell (2003). Based on this modeling, the InSAR deformation pattern provided evidence that primary right-lateral strike-slip motion occurred on the northwest-striking Double Spring Flat fault. A sequence of aftershocks of M 4.9-5.0 occurred along the Double Spring Flat in 1995, but a systematic evaluation of InSAR pairs covering these events failed to reveal any evidence of post-seismic ground deformation.

Adobe Hills

A sequence of three M 5.0-5.6 events occurred in the Adobe Hills area east of Mono Lake in 2004 (Figs. 1, 2). An Envisat pair for14 September 2004 to 3 September 2006 shows a signal associated with these events. A set of elongated fringes is visible across the northeast-trending, left-lateral faults that produced the events. As much as 3 cm of radar line-of-sight (LOS) increase is detectable on the northwest side of the fault, and about 2 cm of LOS shortening is visible on the southeast side. The focal mechanisms for

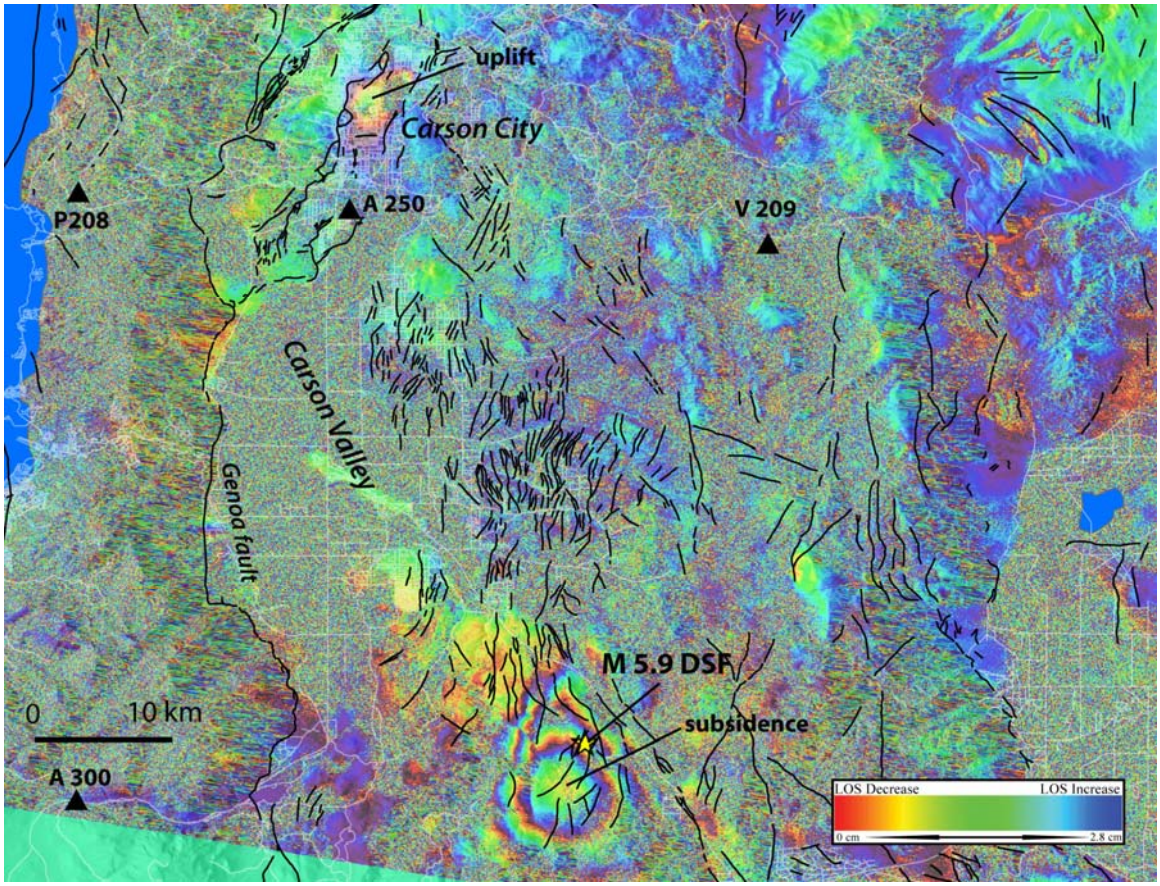


Figure 2. Wrapped interferogram covering the period 11-10-1992 to 4-11-1994.The deformation associated with the M 5.9 Double Spring Flat (DSF) earthquake is visible as multiple 2.8 cm subsidence fringes. A seasonal groundwater signal is visible in Carson City where a full 2.8 uplift fringe is bounded by faults (black lines) of the Carson City (Genoa) fault system. GPS stations shown by black triangles.

these events indicate that the earthquakes were related to left-lateral strike-slip motion on the northeast-striking faults. Based on results obtained from the similar LOS deformation patterns found for the 1994 Double Spring Flat event, we interpret the LOS changes here to reflect primarily vertical deformation across the Adobe Hills fault zone, with subsidence occurring on the northwest side of the fault. However, further study of ascending interferometric pairs would be necessary to determine how much, if any, lateral component of motion contributed to these LOS changes.

North Lake Tahoe

In 2003, a deep swarm of small earthquakes of M <3 were recorded near the north shore of Lake Tahoe. These events were coeval with 6-8 mm of movement on the east side of Lake Tahoe detected by continuous GPS, and the collective sequence of events was interpreted as evidence of lower-crustal magma injection under Lake Tahoe (Smith *et al*.,

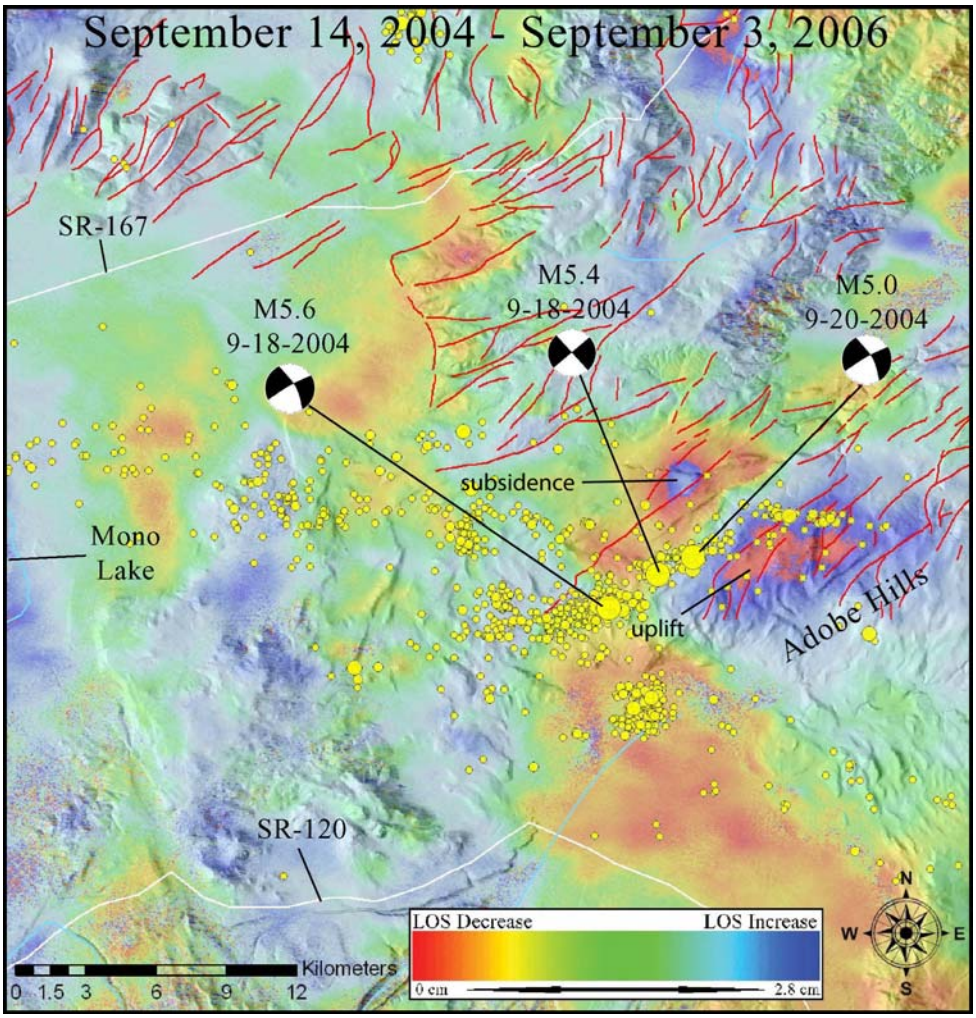
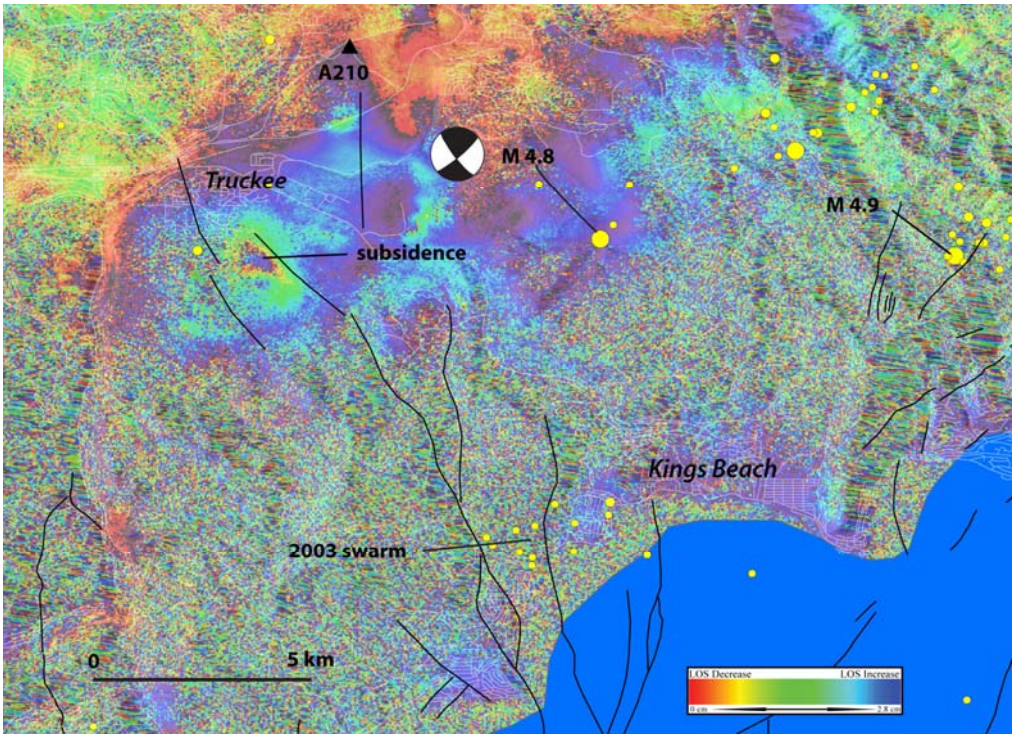


Figure 3. Wrapped interferogram covering the time period 09-14-2004 to 09-03-2006 showing the deformation associated with the 2004 Adobe Hills earthquake sequence. As much as 2.8 cm of apparent subsidence (LOS increase) is visible on the northwest side of the fault zone, and about 2 cm of uplift (LOS decrease) is visible on the southeast side.

2004). These events were preceded by an M 4.9 event in 1998, and they were followed by a similar shallow swarm in the spring of 2005 leading to an earthquake of M 4.8 in June, 2005 (Ken Smith, 2007, personal communication). In an effort to detect any InSAR signal that could be associated with these earthquakes and/or with the displacement of the GPS station SLID, we examined more than 10 InSAR pairs that covered the time of these events.

An InSAR deformation signal was detected along a Quaternary fault in the area of the M 4.8 event south of Truckee, California (Fig. 4). A two-month interferogram covering the June 26, 2005 event shows a 3 cm tear-drop-shaped subsidence signal along a northwest-striking fault about 5 km west of the epicenter. This fault is the northern extension of the structures believed to be associated with the injection-related swarm at the north shore of



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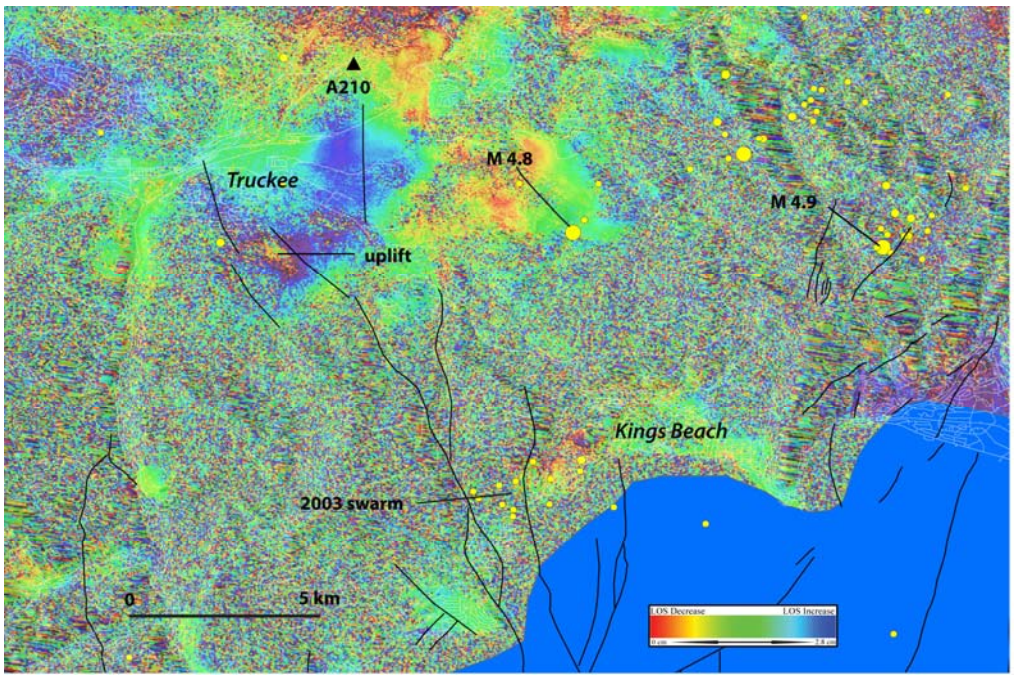


B

Figure 4. Wrapped interferograms showing InSAR deformation signals in the vicinity of the M 4.8 2005 earthquake in the North Lake Tahoe area. A. Interferogram for time period 4-04-2005 to 7-13-2005 showing a full 2.8 cm subsidence fringe in the basin south of Truckee; the signal is bounded by a northwest-striking Quaternary fault with the same orientation as the preferred nodal plane for the 2005 event. B. Interferogram for the time period 9-01-2004 to 5-04-2005 showing a full 2.8 cm uplift fringe in the same location showing subsidence in 2005. Seasonal subsidence and uplift signals indicate that the 2005 InSAR signal is related to groundwater pumping.

the lake. This signal was first believed to indicate that tectonic movement had in fact occurred along this adjacent fault. The InSAR fringe pattern is clearly structurally controlled by the northwest-striking fault, both of which have the same orientation as the preferred northwest-striking nodal plane for the 2005 event (Fig. 4a). We also considered the likelihood that the InSAR signal may have been detecting fault movement precursory to the main M 4.9 event, i.e., possibly associated with the 2005 swarm activity.

However, further investigation revealed that the signal is not tectonic, but it is instead a groundwater-pumping signal associated with municipal wells operated by Placer County, California. Pumping records indicate that heavy pumping was initiated in May, 2005, and that water levels declined by more than 60 m over the next several months. In addition, an interferogram covering the pre-earthquake time period of September, 2004 to May, 2005, indicates that a similar, but reversed, signal (indicating uplift) is present along the fault (Fig. 4b). This uplift clearly indicates that both signals are related to seasonal elastic movement of the aquifer system as pumping is increased during the summer irrigation season.

Groundwater and geothermal fluid signals

Groundwater signals, some of which are quite large, are visible in many of the basins of the study area. In addition to the North Lake Tahoe signal discussed above, groundwater signals were found in the Truckee Meadows (Reno), Carson City, Lemmon Valley, Sierra Valley, Carson Valley, Smith Valley, Warm Springs Valley, and Mason Valley. Persistent subsidence signals are present at the Steamboat and Brady's geothermal areas where significant fluid extraction occurs, and minor subsidence was noted at the Amadee geothermal site in Honey Lake. The following examples are selected in order to highlight the more important signals that reflect long-term pumping activities that may influence motion of nearby GPS stations.

Reno and Carson City

A prominent seasonal groundwater signal is visible in the Truckee Meadows on most InSAR pairs, with 2-3 cm per year of subsidence and uplift depending on the seasonal time periods. The spatial pattern of the signals is apparently structurally controlled by a concealed north-south fault located in the central part of the Truckee Meadows. In some cases, both subsidence and uplift are visible across this structure. In Figure 5, a triangular area of subsidence occurs in the western part of Reno and appears to be bounded by a series of east-west to northeast-trending faults. At the same time, the eastern part of the Truckee Meadows through Sparks exhibits broad uplift. There is also a smaller but persistent seasonal signal visible on multiple interferograms just north of the Chalk Bluffs GPS station (CHLK). In Figure 5, this shows as a 3 cm uplift signal, but comparable subsidence signals are recognized at this location during other time periods. The seasonal repetition of subsidence and uplift in the Truckee Meadows indicates that the aquifer system is responding elastically to seasonal pumping and recharge, and no long-term net subsidence has yet been detected in the time periods studied.

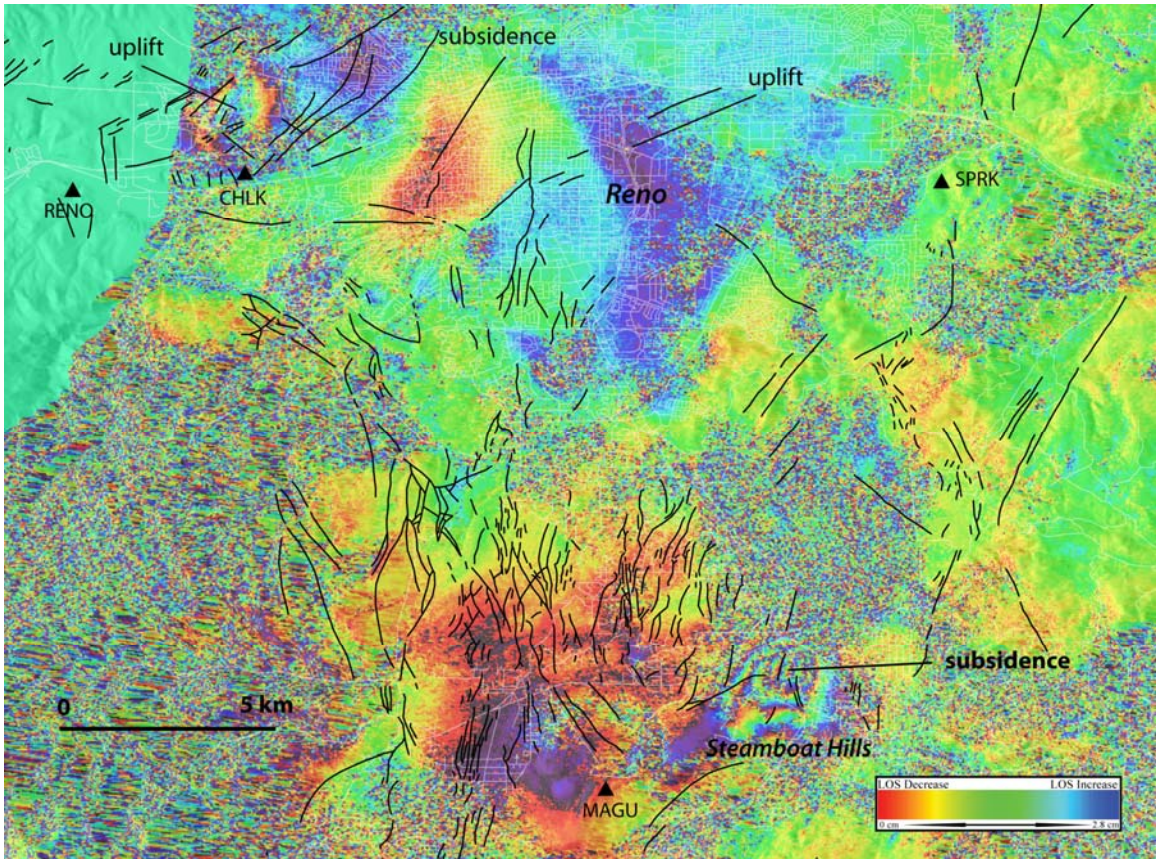


Figure 5. Wrapped interferogram covering the time period 11-10-1992 to 4-11-1996 in the Reno area. A 2 cm subsidence fringe is visible in the western part of the Truckee Meadows and a 1-2 cm uplift fringe is visible in the eastern part. Multiple 2.8 cm subsidence fringes are present in the Steamboat Hills geothermal area; more than 2.8 cm of seasonal uplift occurs in a localized zone north the Chalk Bluff GPS station CHLK.

The most significant continuous subsidence signal occurring in the Reno area is the signal produced by extraction at the Steamboat Hills where subsidence rates are on the order of 2-3 cm per year. In Figure 5, the area west of Steamboat Hills shows a broad area of possible subsidence in the Callahan Ranch area which may either related to geothermal extraction or to domestic groundwater pumping. The GPS station MAGU situated in the Steamboat Hills may be affected by one or both of these signals. The Steamboat Hills signal does not exhibit evidence of seasonal activity and the subsidence is likely a measure of the long-term depressurization and/or cooling of the geothermal reservoir.

Carson City also exhibits a prominent, but smaller, seasonal groundwater signal on most interferograms that is strongly controlled by the faults. On Figure 2, a 3 cm uplift signal is visible in the southeastern part of the valley, bounded on the west by the Carson City segment of the Genoa fault.

Valleys north of Reno

Subsidence signals are visible in several basins in the valleys north of Reno. On a one-year interferogram from 1992-1993 (Fig. 6), multiple (4 or more) fringes in Sierra Valley indicate as much as 12 cm of subsidence during this time, which we attribute to heavy agricultural irrigation pumping. A single fringe of subsidence (~3 cm) is visible in the Stead portion of Lemmon Valley, and a partial fringe is visible in the eastern part of Lemmon Valley. Both signals are controlled by faults, and are likely related to a combination of domestic and irrigation (golf course) pumping. A possible full fringe of subsidence is present at Bordertown in Cold Springs Valley. In Warm Springs Valley, a circular full fringe of subsidence is present in the northern part of the valley, and is likely related to agricultural irrigation pumping.

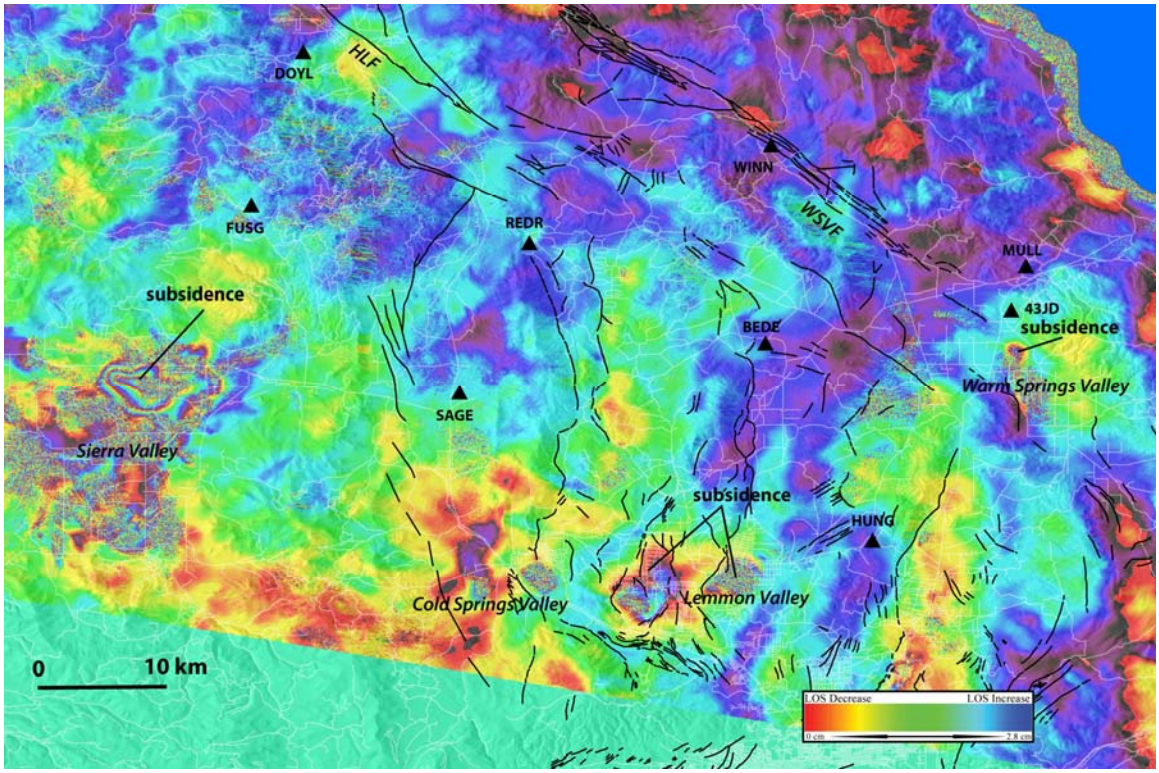


Figure 6. Wrapped interferogram for the time period 3-05-1992 to 6-27-1993 showing groundwater-related InSAR subsidence signals in the valleys north of Reno. A multi-fringe signal is visible in Sierra Valley where it is associated with heavy agricultural pumping. Other groundwater signals are present in Lemmon Valley and Warm Springs Valley. GPS stations shown by black triangles; principal Quaternary faults: HLF, Honey Lake fault; WSVF, Warm Springs Valley fault.

Bradys geothermal site

A prominent, continuous subsidence signal similar to the Steamboat Hills signal occurs at the Bradys Hot Springs geothermal site (Fig. 7). An elongated multi-fringe signal related to geothermal fluid extraction is visible on most interferograms. The signal is structurally controlled by the faults which transect the geothermal site. On this 5-year interferogram, the outer fringes may extend to the GPS station BRAD located southwest of the geothermal site.

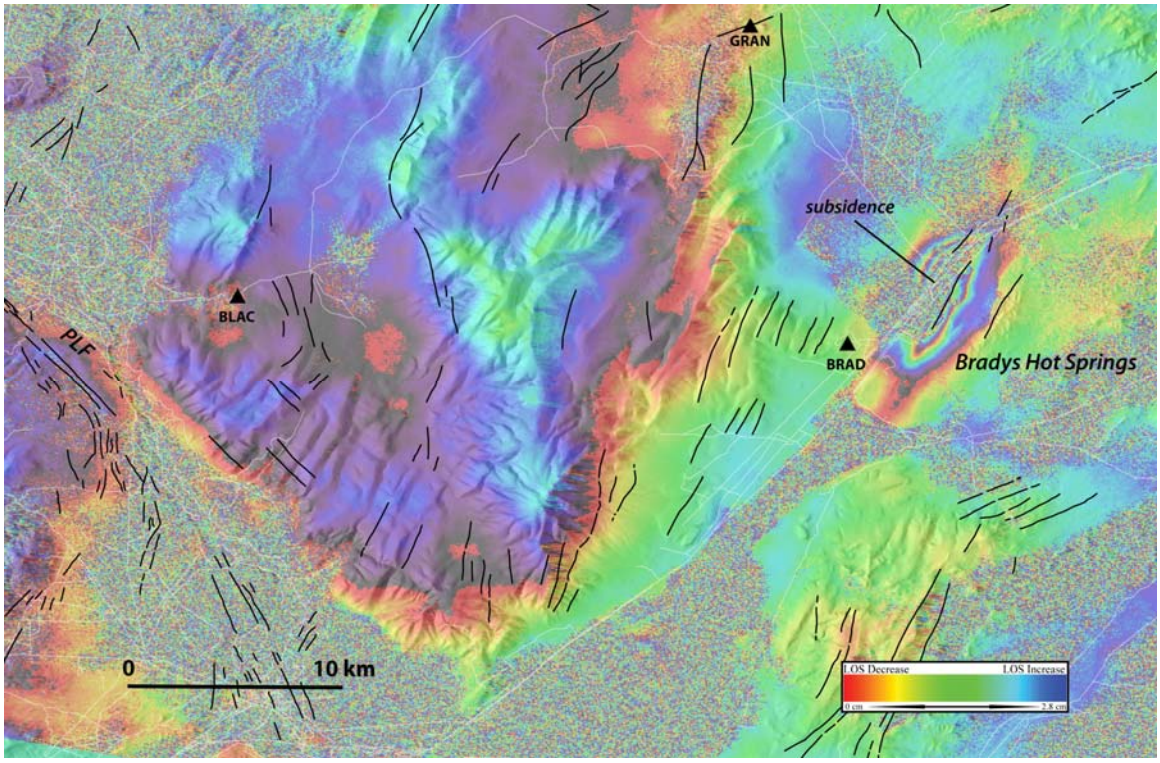


Figure 7. Wrapped interferogram covering the time period 6-06-1997 to 9-13-2002 showing multiple subsidence fringes associated with the Bradys Hot Springs geothermal area. GPS stations shown by black triangles; Pyramid Lake fault, PLF.

Wave-length filtering to improve detection of small amplitude groundwater signals

Interferograms often contain residual linear and quadratic trends which are typically ascribed to orbital uncertainties and ionosphere and regional atmospheric water vapor delays Hanssen (2001). This effect is often seen in ROI_PAC v2.2.2 output, even if simulated orbit refinements are applied. Interferograms partially covering mountainous terrain seem particularly susceptible to containing strong residual trends. Resulting interferograms typically show 1 to 2 residual fringes (3 to 6 cm) across a 100 km scene. Additionally, medium scale atmospheric water vapor patterns add more local signals. These may also include topographic ghosting due to water vapor change. The net effect of these non-surface displacement signals is that true groundwater and tectonic signals on the order of one centimeter may be obscured.

Scene stacking may reduce the variability obscuring a consistent or predictable signal, such as a tectonic displacement, but it is not appropriate if the target signal pattern develops and dissipates over a few months as it does with many groundwater signals. Persistent point scatter approaches depend on an assumed event model and hence cannot reduce noise in short duration single-cycle surface events. To capture single-cycle short duration events or the temporal details within a longer event, we are compelled to use methods that make optimum use of the low-level signals in each interferogram pair. To this end we have developed a wavelength-filtering approach to improve the visualization of small amplitude single-cycle short duration groundwater signals. As a byproduct of this groundwater change detection approach we also produce individual interferograms that offer exceptional sensitivity to local fault displacements or fissure development.

In the wavelength-filtering post-processing approach, the unwrapped LOS surface is flattened using a two step procedure:

1) A least-squares, best-fitting, second-order, six coefficient polynomial surface is removed, creating a residual surface. This procedure removes any linear ramps and quadratic trends.
2) The patterns longer than ~20 km are suppressed through the use of two dimensional Fourier Domain wavenumber filtering using a one-pole high pass with a 10 km filter corner wavelength.

This wavelength filtering achieves several improvements:

1. Cell to cell phase noise is reduced. Ground cell to cell phase noise is reduced in the (60 meter cells) with a one-pole low pass filter with a corner wavelength at 50 meters for detailed local use and 100 meters for the regional presentations.

2. Spatially coherent short wavelength features are highlighted. Spatially coherent short wavelength features are highlighted using synthetic surface shading, i.e., shaded-relief enhancement.

3. Mask-out water vapor induced topographic ghosting. If topographic ghosting is evident in the case of mountains surrounding a basin, we may optionally mask the mountains to leave just the less affected basins for analysis.

Example of wavelength filtering-- Honey Lake area

We performed wavelength filtering on two concatenated Envisat pairs from the Track 27 Frame 2799-2817 swath (Fig. 1) to analyze groundwater signals that are located on the Honey Lake fault: 10 November 2005 to 30 March 2005 and 8 June 2005 to 30 November 2005 (Fig. 8).

The InSAR results on these pairs appear to delineate a hidden fault splay (blue dotted line) diverging to the west-northwest from the Honey Lake fault near Herlong Junction on highway US 395. The inferred splay appears to be expressed as a linear confining "barrier" with ground inflation, temporally followed by deflation, in Figure 9, on it's west side. The subject zone is confined on the west by the Honey Lake fault. A similar size confined zone is present just west of the Honey Lake fault, however, the Honey Lake fault retains local integrity and reverse relief polarity from both flanking zones. The seasonal reversal of polarities eliminates the possibility that that feature is a displacement along the Honey Lake fault, a seismically active structure within the northern Walker Lane belt. Satellite imagery shows that agricultural fields in this area are heavily irrigated.

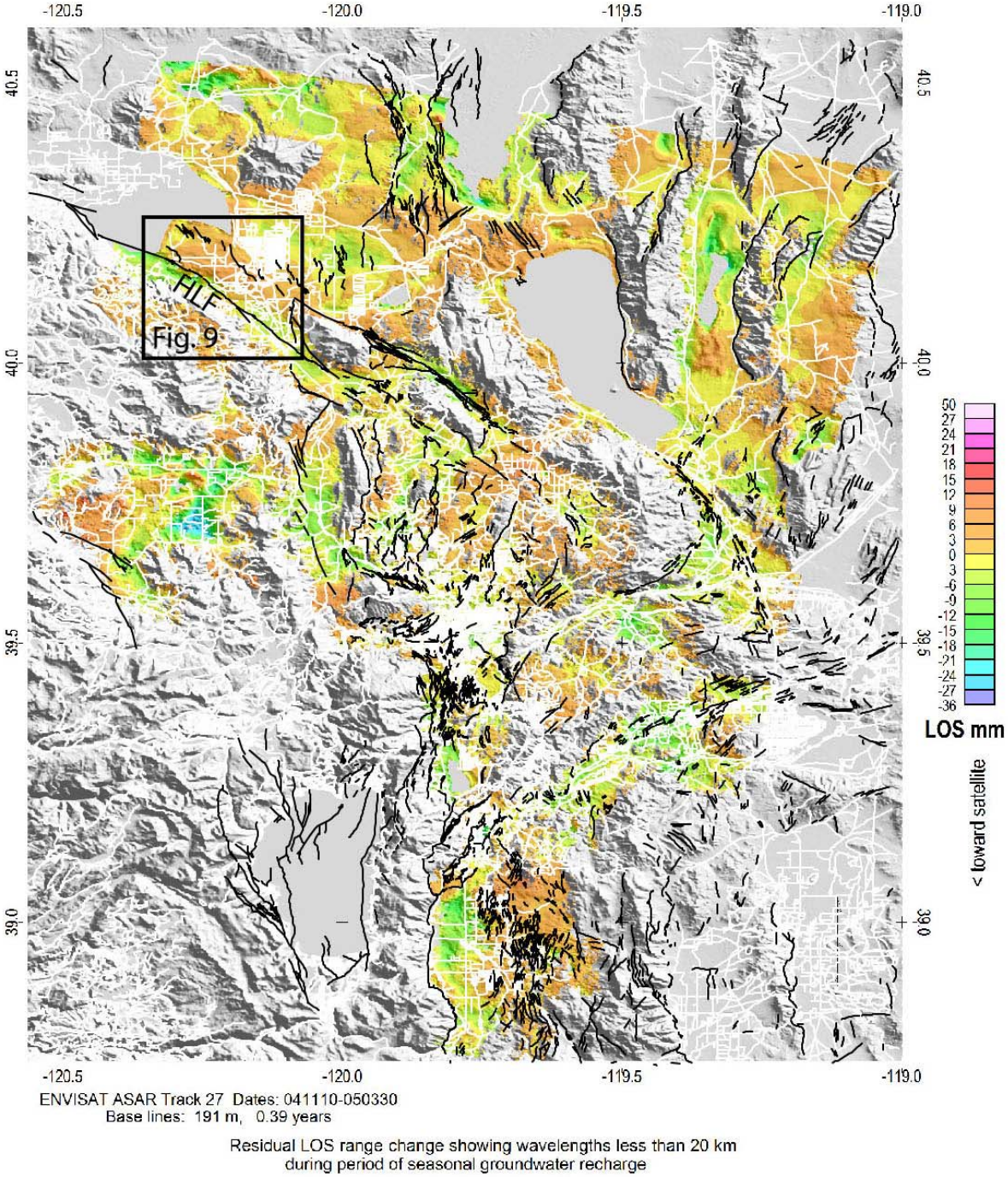


Figure 8a. Residual LOS change interferogram after applying wavelength filtering on Envisat pair 041110-050330. The detected residual signals along the Honey Lake fault (HLF) are shown in Figure 9.

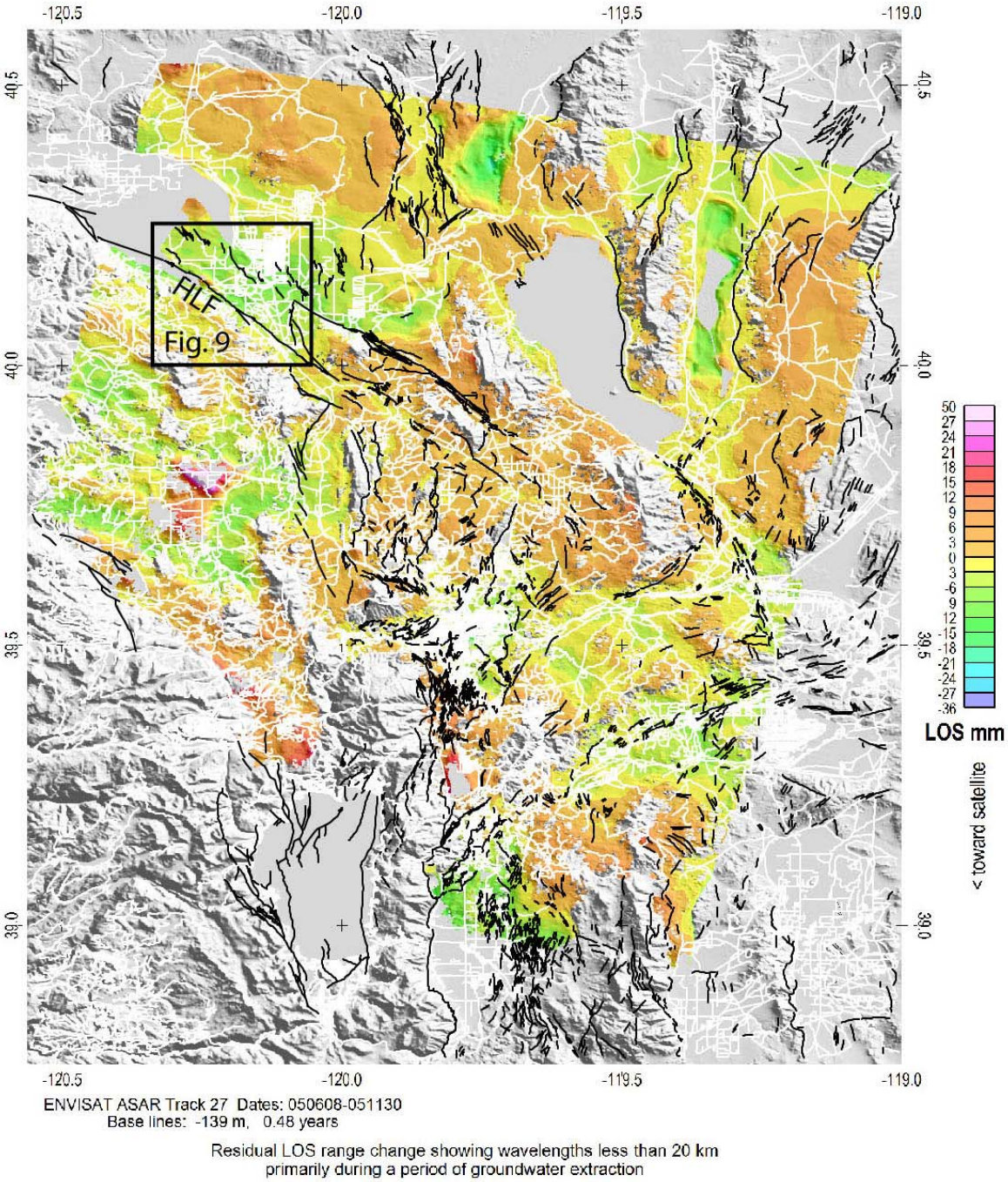
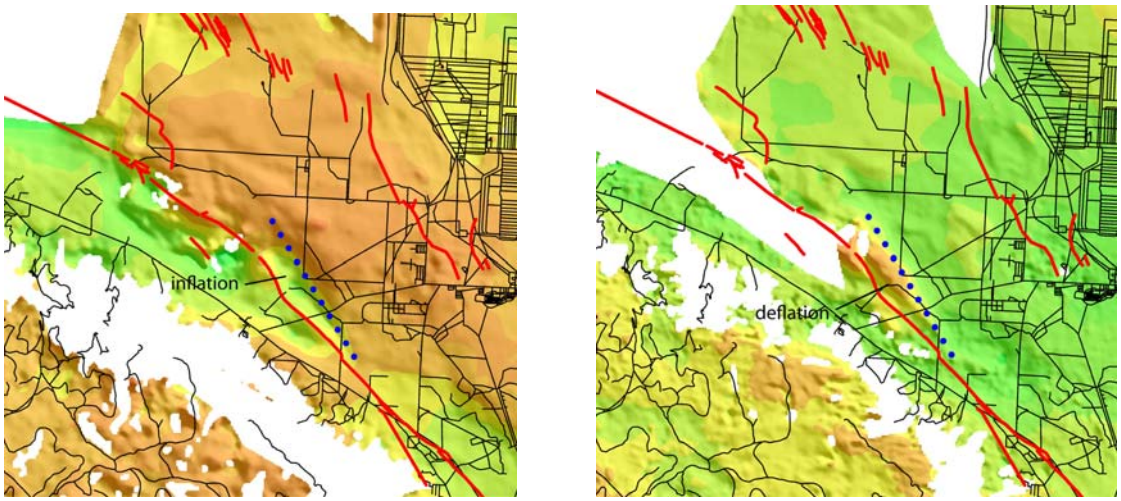


Figure 8b. Residual LOS change interferogram after applying wavelength filtering on Envisat pair 050608-051130. The detected residual signals along the Honey Lake fault (HLF) are shown in Figure 9.



Groundwater recharge period

Groundwater extraction Period

Figure 9. Filtered Envisat interferograms with shaded phase residuals illustrating groundwater recharge and extraction in the Honey Lake area. (Left) Groundwater recharge period showing inflation (green) along the west side of a concealed fault trace (blue dotted line) lying just east of the Honey Lake fault (red line). Interferogram is from dates 041110 and 050330 (Fig. 8a) with time and orbital baselines of 0.39 years and 191 meters respectively. (Right) Groundwater extraction period showing reversed deflation (brown) on the west side of the concealed fault. Interferogram is from dates 050608 and 051130 (Fig. 8b) with time and orbital baselines of 0.48 years and 139 meters respectively.

Principal Findings

This study examined more than 110 InSAR pairs covering the period 1992-2007 in an effort to detect tectonic signals associated with moderate-magnitude earthquakes in the Sierra Nevada-Basin and Range Transition Zone, and to identify and characterize groundwater signals that may influence motion of GPS stations utilized in contemporary strain analyses of the western Basin and Range.

Of 11 earthquakes with magnitudes of M > 4.5 occurring in the area since 1992, we could identify clear InSAR signals with only two sequences, the 1994 Double Spring Flat (M5.9) and the 2004 Adobe Hills (M5.0-5.6) events. The remaining earthquakes, which ranged in magnitude from 4.6 to 5.0, did not show any signals on multiple InSAR pairs covering the time of the events. No InSAR signals were found associated with the M 5 aftershocks in the Double Spring Flat area, precluding any significant post-seismic surface deformation.

We also searched specifically for two M 4.8-4.9 events possibly associated with deep magma injection in the North Lake Tahoe area, and found no evidence of tectonic surface deformation. A fault-controlled InSAR signal in the epicentral region during the time of

the 2005 event was shown to be a groundwater signal. Interferometric coherence was generally poor in this region on all interferograms due to high terrain, tree cover, and seasonal snow, resulting in persistent incoherence over much of the high Sierra and in particular over the GPS station on Slide Mountain which showed movement in 2003 and 2005.

Our earlier studies in southern Nevada basins suggested that earthquakes in the magnitude range of M 4.5-5.0 are detectable with InSAR; we successfully detected several centimeters of deformation associated with the 1999 M 4.9 Frenchman Flat earthquake (Katzenstein and Bell, 2005). The failure to detect similar-magnitude signals in the Sierra Nevada region may be attributable to less favorable interferometric conditions, including high terrain, vegetative cover, and snow, as well as to the possibility that these events had deeper focal depths with no significant ground movement. In the future, the use of L-band radar presently being acquired by the Japanese ALOS satellite will potentially allow better detection of tectonic signals in such heavily vegetated terrain.

We found no InSAR signals along the Pyramid Lake fault which was the location of numerous M 2-4 earthquakes and an M 4.6 event in 1993. Interferometric coherence was generally good through this region of the study area on all interferometric pairs.

InSAR signals were detected along the Honey Lake fault on pairs from 2004-2005. In an effort to carefully analyze the nature of this signal, we performed wavelength filtering on the LOS results to remove long wavelength phase data. The phase residuals indicated that this signal was a groundwater signal and not related to tectonic motion of the fault.

We found that numerous groundwater signals were present in many of the basins of the study area, and that the spatial pattern of many of these signals is determined by structural (fault) control. Large, prominent seasonal pumping (subsidence) and natural recharge (uplift) signals are present in the Truckee Meadows and in Carson City, with smaller signals occurring in other valleys to the north of Reno.

Geothermal fluid extraction occurring at Steamboat Hills and Bradys Hot Spring has resulted in continuous long-term contraction of the geothermal reservoir and subsidence on the order of 3 cm or more per year. These InSAR signals may affect movement of GPS stations that are located adjacent to the observed deformation.

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