MONITORING TIME-DEPENDENT VOLCANIC DYNAMICS AT LONG VALLEY CALDERA USING INSAR AND GPS MEASUREMENTS

Zhen Liu, Danan Dong, Paul Lundgren
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109 USA

ABSTRACT

Continuous monitoring Long Valley Caldera since the late 1970s, including data from seismic and geodetic networks has shown renewed episodic unrest activities with accelerated uplift separated by reduced uplift, no activity or slow deflation. We examine the time-dependent behaviors at Long Valley Caldera in 1996-2009 by integrating InSAR and continuous GPS (CGPS) measurements. The ERS-1/2 radar data between 1992 and 2008 and reprocessed three-component continuous GPS (CGPS) data from Long Valley GPS network in 1996-2009 were combined to invert for source geometry and volume change in the following deformation episodes: 97-98 uplift, 02-03 uplift, 04-07 slow subsidence, and 07-09 slow uplift. Our results show that all post-2000 events locate in the shallow depth range of ~7-9 km and have nearly identical source location, suggesting that these events are caused by the same partial melt magma source at the mid-crustal level. All three events are characterized by the low volume change, in comparison with previous 1997-1998 inflation event that has much larger volume change and steeper source geometry. If we regard post-2000 events as proxy for future eruption hazard, the inferred source dynamics (e.g., mid-crustal location and low volume change) from these post-2000 events suggest that the probability for near-term eruption is low. Our study demonstrates that CGPS, along with InSAR, are important tools in monitoring time-dependent source process at the active volcano region.

***Index Terms*—**Geophysical inversion problems, Geodesy, Radar imaging, interferometry, Global Positioning System

1. INTRODUCTION

The Long Valley Caldera, situated at the eastern edge of the Sierra Nevada block, has been active for the past several million years (Figure 1). Geodetic measurements since the late 1970s, including data from precise leveling, global positioning system (GPS), and two-color electronic distance meter (EDM) has shown renewed unrest activity at Long Valley Caldera with episodic uplift and subsidence [1]. Since 2000, continuous GPS network in the region has recorded a new series of inflation and deflation episodes (Figure 2). These non-secular deformation events typically have much smaller amplitudes with regard to the previous 1997-1998 uplift. A thorough understanding of these most recent episodic events and how they relate to the pre-2000 inflation (e.g., 1997-1998 event) is critical in addressing the important questions regarding the dynamics of the Long Valley volcano. For example, do the recent recurrent uplift and subsidence at Long Valley Caldera have the same source mechanism as ones prior to 2000? What is their implication towards near-term volcanic hazard in the region?

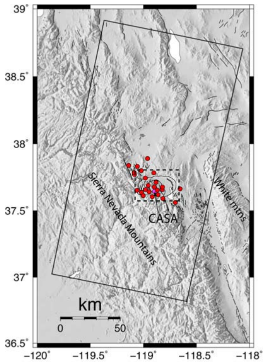

Fig.1 Shaded relief map of Long Valley Caldera region. Filled red circles are GPS site location. Large rectangle box is the coverage of the ERS-1/2 SAR image. Dashed box is the model fit area. Also indicated is the GPS site CASA whose position time series is shown in Fig2.

In this paper, we perform the first comprehensive study on the source processes of these post-2000 events. We also revisit the inflation event during 1997-1998. We combine continuous GPS (CGPS) data and ERS-1/2 satellite data from European Space Agency (ESA) between 1996 and 2008 to model source process of 97-98 uplift, 02-03 uplift, 04-07 slow subsidence, and 07-09 slow uplift. Based on the modeling results, we examine the time-dependent behaviors of the Long Valley Caldera, and discuss the implication for the near-term volcanic eruption hazard in the region.

2. DATA ANALYSIS

We use the combined CGPS solutions from NASA MEaSUREs Earth Science Data Records system [2]. The CGPS position time series in 1996-2009 are realized in ITRF2005 reference frame, and show clear deformation signals over different periods (Figure 2). We perform time series analysis to estimate seasonal variation, earthquake and hardware related jumps, linear rates, and non-secular transient signals [3]. We estimate and remove common mode error through principal component analysis (PCA) [4]. The non-secular rates and uncertainties for the 97-98 uplift, 02-03 uplift, 04-07 slow subsidence, and 07-09 slow uplift in the periods of 1997.6-1998.6, 2002-2003.5, 2004.0-2007.0 and 2007.0-2009.8 are estimated using CATS [5]. These rates and derived displacements at different time periods are used jointly with InSAR measurements to model volcanic source dynamics.

We processed the satellite synthetic aperture radar (SAR) data acquired by the European Space Agency's ERS-1 and 2 satellites between 1992/06/04 and 2008/08/03 from descending track 485, frames 2835 using JPL/Caltech ROI_PAC. We select the InSAR pairs with small perpendicular baselines (< 200 m) and short

978-1-4244-9566-5/10/$26.00 ©2010 IEEE

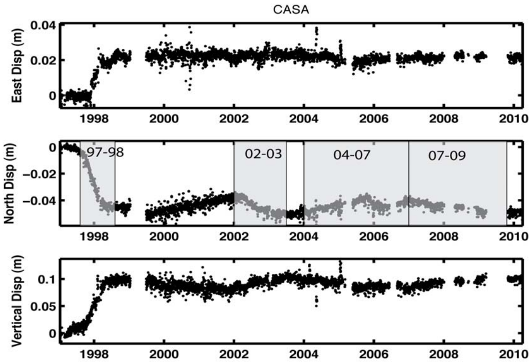

Figure 2. East, north, up-component of GPS position time series of CASA. Four unrest periods are indicated.

temporal separations (< 4 years). We estimate and remove the topographic and orbit geometry phase contribution using the SRTM 3-arcsec digital elevation and the precise orbits. We then unwrapped each interferogram using the program SNAPHU_mcf [7]. For 1997-1998 event, we applied SBAS algorithm to estimate the line of sight (LOS) displacement time series and mean LOS rate at each pixel [8]. For post-2000 deformation events, we identified two interferograms that have deformation signals corresponding to the 2002-2003 uplift (pair 01/09/09-03/06/01) and 2004-2007 slow subsidence (pair 04/10/03-07/07/15). We mask out the low coherence area and the area that is affected by local geothermal activity. We then applied a quadtree algorithm to subsample the masked unwrapped interferograms [9]. The decimated InSAR phase map are then used in the subsequent modeling. The variance of the resulting subsampled InSAR data is calculated based on the root-mean-square (RMS) values of quadtree squares.

.

3. MODEL METHOD

Previous studies on the 1997-1998, 2002-2003 uplift events indicate that the intrusion beneath the resurgent dome may be cigar-shaped [e.g., 10, 11, 12, 13]. So we assume the most recent deformation episodes since 2000 are caused similarly by a finite ellipsoidal source. The analytical formulation for the prolate spheroid [14] in an elastic, homogeneous, isotropic half-space is used in this study, in which the source model is defined by three source location parameters (x, y, z), strike, plunge, semi-major axis a, axis ratio b/a, and normalized excess pressure. We seek to minimize the reduced Chi-square χ_r^2 in parameter optimization. The χ_r^2 measure accounts for both the complexity of the model and the appropriateness of data error.

We use a nonlinear Monte Carlo random-cost (RC) approach to solve for optimal model parameters. The RC approach samples the model parameter space within *a priori* parameter bounds and search for the regions with lowest model costs [15, 16]. It enforces a random walk in the misfit space thus can overcome the local minima. To ensure a global solution, a large number of trial models (O(~10^5)) is enforced by combining randomized priori model and random walk when exploring the misfit space. Synthetic benchmark tests show that this approach can successfully retrieve the source parameters.

4. RESULTS

We combine both InSAR and GPS data to invert for the source parameters of the 97-98 uplift, 02-03 uplift, and 04-07 subsidence events. For the 97-98 uplift, we use estimated mean LOS deformation rate during 96/06/01-98/11/29 and GPS velocity estimates in the same period. For 02-03 uplift and 04-07 slow subsidence, we use the LOS displacement, along with GPS displacement vectors in the same time period, in the inversion. The GPS displacements for the 2004-2007 event are derived in the period of 2004/10/03-2007/07/15 by correcting effects due to slow subsidence in 2004/01/01-2004/10/03 and slow uplift in 2007/01/01-2007/07/15. For the 07-09 slow inflation, we only use GPS data to invert for the source parameter as there are no identifiable InSAR signals.

We experiment the different weighting between the InSAR and GPS data, in addition to their formal uncertainty errors. After considerable experiments, we find that for the 02-03, an equal weight between GPS and InSAR gives reasonable fit to both GPS and InSAR data (Figure 3).

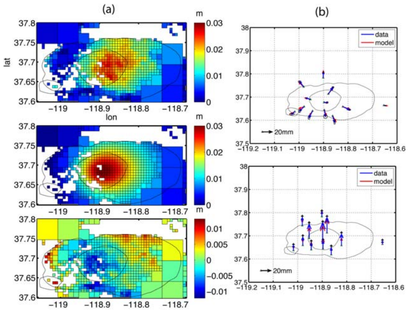

Figure 3. For 02-03 uplift, (a) top to bottom, InSAR LOS displacement, model fit and residual; (b) GPS horizontal and vertical data (blue) vs. model fit (red).

For the 04-07 deflation, a GPS:InSAR weight of 2:1 provides a good fit to both data although a weight of 1:1 yields a similar source but has a reduced fit to the GPS data (Figure 4).

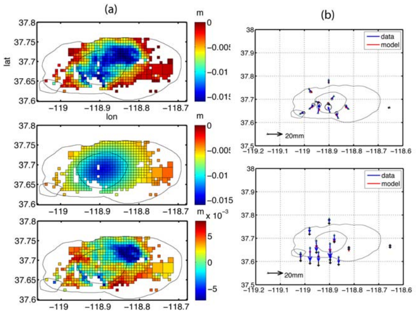

Figure 4. For 04-07 subsidence, (a) top to bottom, InSAR LOS displacement, model fit and residual; (b) GPS horizontal and vertical data (blue) vs. model fit (red).

For the 97-98 inflation, a GPS:InSAR weight of 1: 2 provides reasonable fit to both data (Figure 5).

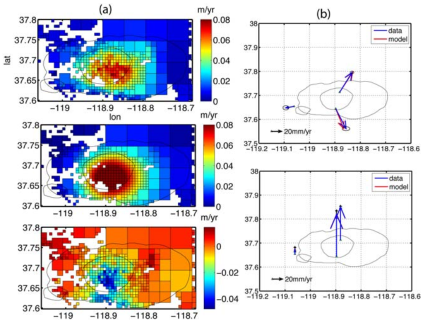

Figure 5. For 97-98 uplift, (a) top to bottom, InSAR LOS displacement, model fit and residual; (b) GPS horizontal and vertical data (blue) vs. model fit (red).

It should be noted that despite the different weighting between InSAR and GPS and resultant optimal source parameters, the sources of 97-98, 02-03, and 04-07 events are generally well resolved to the depth range of ~7-9 km, with source position consistently centered in the western portion of the caldera. The inferred volume changes are ~0.01, ~-0.003, and ~0.03 km^3 for the 02-03, 04-07, and 97-98 events, respectively. Table 1 gives the fit for the optimal source parameters of all post-2000 events.

Table 1. Source parameters

	97-98	02-03	04-07	07-09
GPS-χ^2	3.12	6.00	4.96	4.64
InSAR-χ^2	2.38	3.15	8.62	N/A
X(°)	-118.91	-118.9	-118.92	-118.89
Y(°)	37.67	37.69	37.69	37.69
Z(km)	7.32	9.82	7.99	8.24
$\Delta P/\mu$	5.37E-03	5.98E-05	-6.16E-04	8.2E-05
a (km)	1.94	7.54	5.60	9.47
b/a	0.46	0.42	0.1	0.16
Strike (°)	76.08	136.94	112.72	99.58
Plunge (°)	126.51	110.61	10.49	169.66
ΔV(km^3)*	0.0261	0.0142	-0.0034	0.0056

* Derived from $\Delta P/\mu$, a, and b/a

5. CONCLUSION

Our preferred models for the post-2000 episodes include a steeply dipping source for the 02-03 inflation and nearly horizontal dipping sources for 04-07 deflation and 07-09 inflation (Table 1). Whether these post-2000 inflation and deflation involves the magma movement or local hydrothermal fluid perturbation requires additional constraint. Even though we cannot exclude the fluid influence completely, the consistent location of these unrests and the similar source depth suggest that these events could be caused by the same process beneath the resurgent dome.

The resolved volume changes for the 02-03 inflation, 04-07 deflation, and 07-09 inflation from the inversion of InSAR and GPS data are ~0.01, ~-0.003, and ~0.006 km^3, much smaller than ~0.03 km^3 during 1997-1998 inflation. The reduced strength and accompanied quiescence in seismic activities suggest that the Long Valley Caldera currently is not in a heightened activity stage. If we regard these post-2000 events as proxies for the future eruption hazard, the source geometries, mid-crustal location and low volume changes suggest the probability for near-term eruption is low.

Our study indicates that integrating CGPS and InSAR are important tools in monitoring time-dependent source dynamics of active volcanoes.

ACKNOWLEDGMENT

We thank the European Space Agency for ERS data provided through the UNAVCO WInSAR archive. The research described in this paper was supported under contract with the National Aeronautics and Space Administration at the Jet Propulsion Laboratory, California Institute of Technology.

6. REFERENCES

[1] D. P. Hill, Unrest in Long Valley caldera, California, 1978-2004, *in* De Natale, G., et al., eds., Mechanisms of activity and unrest at large calderas: Geological Society of London Special Publication 269, p. 1-24, 2006.

[2] Downloadable from http://geoapp03.ucsd.edu/gridsphere/gridsphere.

[3] Z. Liu, S. Owen, D. Dong, P. Lundgren, F. Webb, E. Hetland, M. Simons, 2010, Estimation of interplate coupling in the Nankai trough, Japan using GPS data from 1996 to 2006, doi:10.1111/j.1365-246X.2010.04600.x.

[4] D. Dong, P. Fang, Y, Bock, F. Webb, L. Prawirodirdjo, S. Kedar, P. Jamason, Spatio-temporal filtering using principal component analysis and Karhunen-Loeve expansion approaches for regional GPS network analysis, *J. Geophys. Res.,* 111, B03405, doi: 10.1029/2005JB003806, 2006.

[5] S. D. P. Williams, Y. Bock, P. Fang, P. Jamason, R. M. Nikolaidis, L. Prawirodirdjo, M. Miller, D. J. Johnson, Error analysis of continuous GPS position time series, *J. Geophys. Res.,* 109, B03412, doi:10.1029/2003JB002741, 2004.

[7] C. W. Chen, and H. A. Zebker, Two-dimensional phase unwrapping with use of statistical models for cost functions in non-linear optimization, *J. Optical. Soc. Amer., 18*, 338-351, 2001.

[8] P. Berardino, R. Lanari, E. Sansosti, A new Algorithm for surface deformation monitoring based on small baseline differential SAR interferograms, IEEE Transactions on Geoscience and Remote Sensing, 40, 11, 2375-2383, 2002.

[9] S. Jónsson, H. A. Zebker, P. Segall, F. Amelung, Fault slip distribution of the 1999 Mw7.2 Hector Mine earthquake, Clifornia, estimated from satellite radar and GPS measurements, *Bull. Seism. Soc. Am.*, 92(4), 1377-1389, 2002.

[10] Y. Fialko, M. Simons, Y. Khazan, Finite source modeling of magmatic unrest in Socorro, New Mexico, and Long Valley, California, *Geophys. J. Int.,* 146, 191-200, 2001.

[12] P. Tizzani, M. Battaglia, G. Zani, S. Atzon, P. Berardino, R. Lanari, Uplift and magma intrusion at Long Valley caldera from InSAR and gravity measurements, Geology, 37, 1, 63-66, doi:10.1130/G25318A.1, 2009

[13] L. Feng and A. Newman, Constraints on continued episodic inflation at Long Valley Caldera, based on seismic and geodetic observations, J. Geophys. Res., 114, B06403, doi:10.1029/2008JB006240, 2009.
[14] X. M. Yang, P. M. Davis, J. H. Dietrich, Deformation from inflation of a dipping finite prolate spheroid in an elastic half-space as a model for volcanic stressing, *J. Geophys. Res.*, 93(B5), 4249-4257, 1998.
[15] B. Berg, Locating global minima in optimization problems by a random-cost approach, *Nature,* 361, 708-710. Berg, 1993