Continuation of Survey GPS Measurements and Installation of Continuous GPS Sites at The Geysers, California, For Geothermal Deformation Monitoring

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Summary

The Geysers is a geothermal power production field in northern California, about 100 miles north of San Francisco. Geodetic measurements over the period 1994 to 2011 show rapid subsidence and contraction, as first observed with terrestrial leveling measurements in the 1970s (Lofgren, 1981). We present evidence of the rate of subsidence reducing in the 2000s compared to the 1990s using episodic ("survey") Global Positioning System (GPS) and interferometric synthetic aperture radar (InSAR) observations.

Furthermore, two continuously-operating GPS sites were installed by the authors in winter 2012–2013. A few months of data from these sites suggests a reversal of the dominant deformation pattern of contraction and subsidence to one of uplift and dilation around the Northwest Geysers, where an Enhanced Geothermal Systems (EGS) demonstration project began in October 2011. Continuous GPS data from a nearby Plate Boundary Observatory (PBO) site shows a change in velocity at approximately this time.

We seek partnerships with industry and other agencies to continue and expand continuous GPS monitoring of The Geysers. We intend to use this data to observe the deformation and investigate the mechanics of the reservoir. Successful monitoring and modeling of the deformation will address key questions regarding the sustainability and efficiency of power production, stimulated or otherwise.

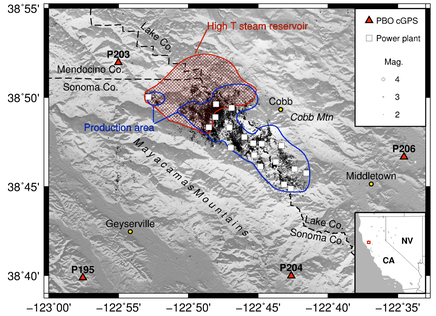


Figure 1 *Overview of The Geysers geothermal field in northern California, in the Mayacamas Mountains on the borders of Sonoma, Lake and Mendocino Counties. Approximate production area and high-temperature steam reservoir boundaries are from Beall et al. (2010, Figure 3). Seismicity is from Waldhauser and Schaff (2008), and updates thereof from http://www.ldeo.columbia.edu/~felixw/NCAeqDD/.*

Survey GPS in the 1990s and 2000s

Groups including Stanford University, the University of Utah, University of California, Berkeley and University of California, Riverside, have made episodic GPS observations of geodetic marks within The Geysers from 1994 to the present. These measurements provide precise crustal velocities (Figure 2).

Wastewater injection programs started in October 1997 (Southeast Geysers Effluent Pipeline; SEGEP) and November 2003 (Santa Rosa-Geysers Recharge Project; SRGRP) may have changed the pattern and rate of deformation (Figures 3 and 4), although this is difficult to ascertain with few data points.

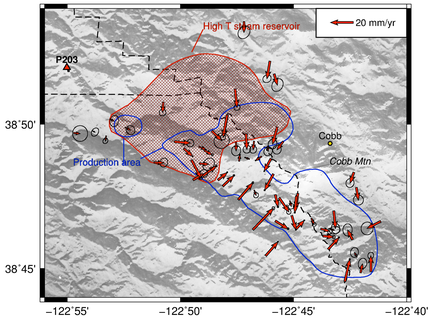
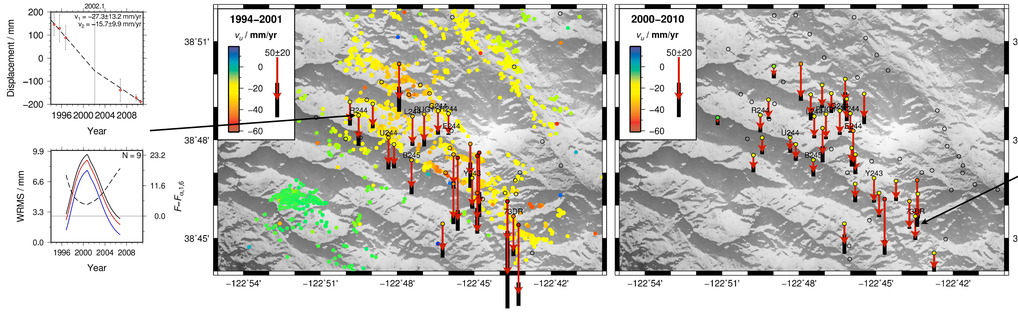
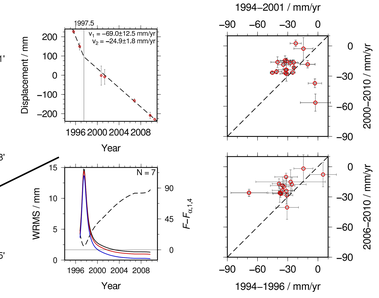


Figure 2 *Horizontal velocities within The Geysers from survey GPS observations in the period 1994 to 2011. Production area and high-temperature steam reservoir are marked as in Figure 1. The velocities are given in a reference frame that minimizes the velocity of local sites outside the production area. In this velocity reference frame, localized contraction is clear.*





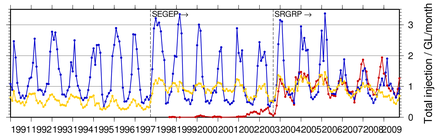


Figure 3 *Wastewater injection history. Steam condensate has been reinjected throughout much of the production history of The Geysers. Two external water sources were added in October 1997 (SEGEP) and November 2003 (SRGRP). Colors are for arbitrarily-chosen injection groupings in the central Geysers (blue), southern Geysers (yellow; mostly influenced by SEGEP) and the northern Geysers (red; mostly influenced by SRGRP).*

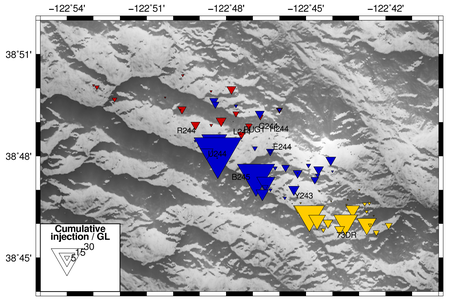
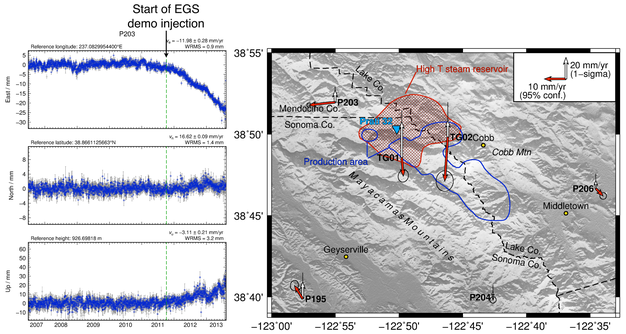


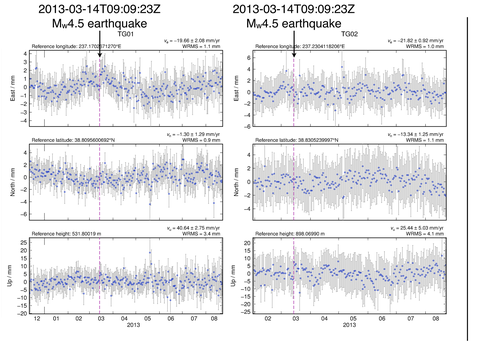
Figure 4 *Vertical velocities of survey GPS sites for the period 1994–2001 and 2000–2010 and PS-InSAR results from Vasco et al. (2013). Outset figures show vertical time series (top panel) and likelihood of a velocity change at using the result of an F-test where the null hypothesis is that no velocity change occurs (bottom panel). Black line shows the 90% confidence interval, red shows 95% confidence and blue shows 98%. Some sites (e.g. 73DR, right) show a clear preference for a change in velocity around the time of a local wastewater injection project start (see Figure 3). Others (e.g. R244, left) do not have the temporal resolution to determine this with any confidence, hence the need for continuous GPS monitoring. Ratio plot on far right shows the difference between vertical rates for the periods shown on the axes. A reduction in the rate of subsidence is generally seen throughout the field from the 1990s to 2000s.*

Continuous GPS

Continuous GPS provides high-temporal resolution to monitor and investigate the precise timing of changes in deformation pattern, which is not possible using episodic observations such as survey GPS or any InSAR techniques. This may be extended to high-rate data collection for "GPS seismology," which measures displacement directly. (TG01 and TG02 currently record at a rate of 10 Hz.) Continuous GPS also provides accurate and reliable 4-D geo-referencing for other techniques such as InSAR.

Figure 5 ➔ *Time series and velocities for data since the beginning of 2013. Time series velocity annotations are relative to North America; map velocities are in the same local reference frame as Figure 2. Horizontal velocities are red and vertical velocities are white. These velocities show uplift and dilation, possibly as a result of the Enhanced Geothermal Systems demonstration project started at the Prati 32 well in October 2011.*





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