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 5).

Wastewater injection programs started in October 1997 (Southbay Geysers Efficient Riparian; SEGEP) and November 2003 (Santa Rosa-Geyers-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.

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 (TGG1 and TGG2 currently record at a rate of 10 Hz). Continuous GPS also provides accurate and reliable 4D geo-referencing for other techniques such as InSAR.


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References


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 Beck et al. (2010). Figure 3: Seismicity is from Wildhauer and Schwab (2008), and updates from http://www.lds.colorado.edu/~felixw/ACGAC2/50.

Figure 2 Horizontal velocities within The Geysers from survey GPS observations in the period 1994 to 2011. Production area and high-temperature steam reservoir boundaries are from Beck et al. (2010).

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 arbitrarily-chosen injection groupings in the central Geysers (blue), southern Geysers (red, mostly influenced by SEGEP) and the northern Geysers (yellow; mostly influenced by SEGEP) and the northern Geysers (yellow; mostly influenced by SEGEP). Some sites (e.g. 73DR, right) show a clear preference for a change in velocity at the time of a detailed wastewater injection project start (see Figure 2). Others (e.g. 224R, 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 x-axis. Reduction in the rate of subsidence is generally seen throughout the field from the 1990s to 2000s.

Figure 4 Vertical velocities of survey GPS sites for the period 1994–2000 and 2000–2010 and PS-InSAR results from Vecki et al. (2008). Outline figures show vertical time series data for a PS-InSAR site and a survey GPS site (left 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 99%.

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

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References


