A Reduction in the Rate of Subsidence Observed at The Geysers Geothermal Field, Northern California, Between 1994 and 2010

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Introduction

The Geysers geothermal field in northern California has been commercially productive since 1960. After peak power production in the 1980s, steam pressures and yield declined. The Geysers is an Enhanced Geothermal System (EGS) where re-injection is used to stimulate and sustain the reservoir's yield. We present geodetic data and statistical analysis that shows injection activities have had a measurable effect on the deformation within The Geysers.

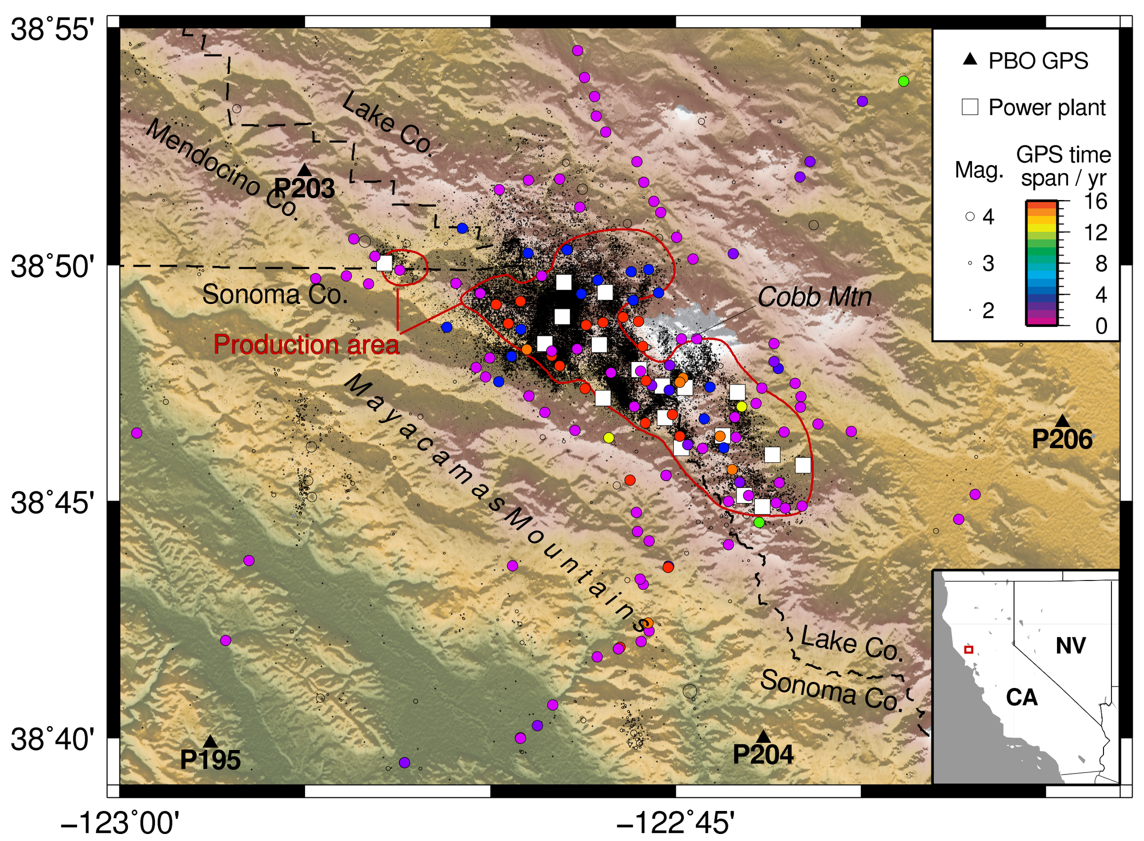


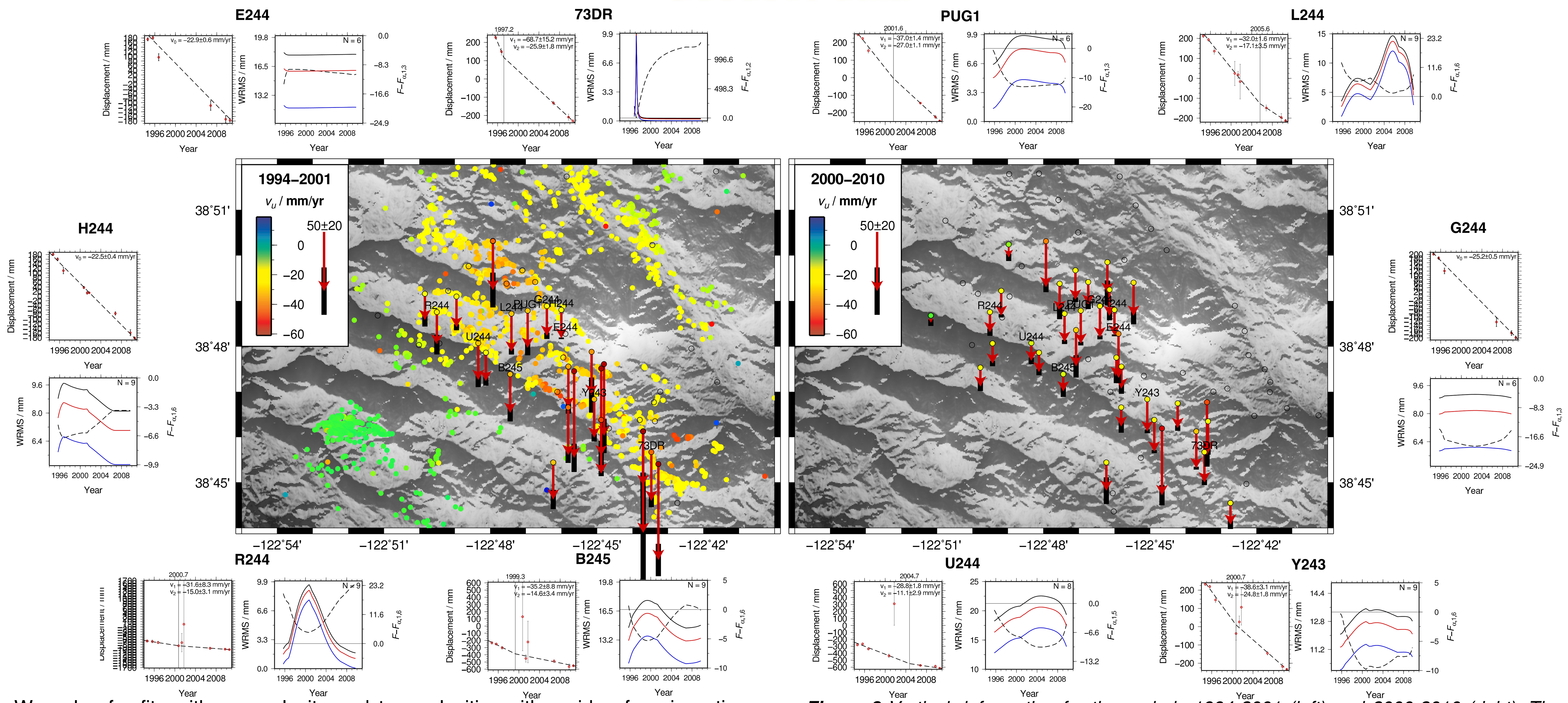
Figure 1 *Location and layout of The Geysers. Seismicity is high but of low magnitude and generally confined to the active geothermal region. Survey GPS sites are dense within The Geysers and extend along main roads outside the area, and are colour-coded by length of time series available. (Sources of data: Northern California Earthquake Data Center, seismicity; Calpine Corporation, power plants; Beall et al., 2010, production area.)*

Survey	Epoch	Institution
The Geysers 1994/08	1994/08/07–1994/08/13	Stanford (UNAVCO)
The Geysers 1994/09	1994/09/26–1994/10/01	Stanford (UNAVCO)
The Geysers 1995	1995/08/04–1995/08/11	Stanford (UNAVCO)
The Geysers 1996	1996/09/21–1996/09/27	Stanford (UNAVCO)
The Geysers 2000	2000/09/10–2000/09/17	University of Utah
The Geysers 2001/04	2001/04/25–2001/05/02	University of Utah
The Geysers 2001/09	2001/09/10–2001/09/28	University of Utah
The Geysers 2006	2006/10/04–2006/10/23	U. Utah / UC Berkeley
The Geysers 2009	2009/09/18–2009/09/24	UC Riverside
North SF Bay 2010	2010/07/13–2010/07/23	UC Riverside

Table 1 *Summary of contributing GPS surveys. Stanford surveys are all publicly available from the UNAVCO archive and the results published in Mossop and Segall [1997,1999]. The 2000 and 2001 surveys were conducted with short occupations and processed using the L1 and L2 phase independently rather than in an ionosphere-free combination. GJF was at UC Berkeley during the 2006 survey.*

Due to the sparsity of data and the questionable nature of the short occupations during 2000 and 2001, we restrict our analysis to reliable sites; that is, those which were measured at least four times in 1994, 1996, 2006 and 2010. This provides us with the best coverage and quality for detecting changes in the rates of subsidence.

Geodetic data



We solve for fits with one velocity and two velocities either side of a given time, which is varied between 1994 and 2011. These models are compared using an F-test where the F-statistic is defined as $F = \frac{\chi_1^2 - \chi_2^2}{\nu_1 - \nu_2} / \frac{\chi_2^2}{\nu_2}$, where χ_i^2 is the sum of the weighted squared residuals to model i and ν_i is the number of degrees of freedom, α = 10% (black), 5% (red) and 2% (blue), and N is the number of data used in the regression calculation. The quantity plotted on the y-axis must be positive to be statistically significant.

Figure 2 *Vertical deformation for the periods 1994-2001 (left) and 2000-2010 (right). The projected component of PS-InSAR data from ERS descending track 113 over the period 1992/06/13 to 1999/09/14 is included in the left figure. GPS sites are shown by vertical vectors with 1-sigma error bars and an outlined circle coloured according to the PS-InSAR scale bar. Outset figures show example time series from several good quality sites and their accompanying F-test results, given a fixed time of change of rate (see main text).*

Injection history

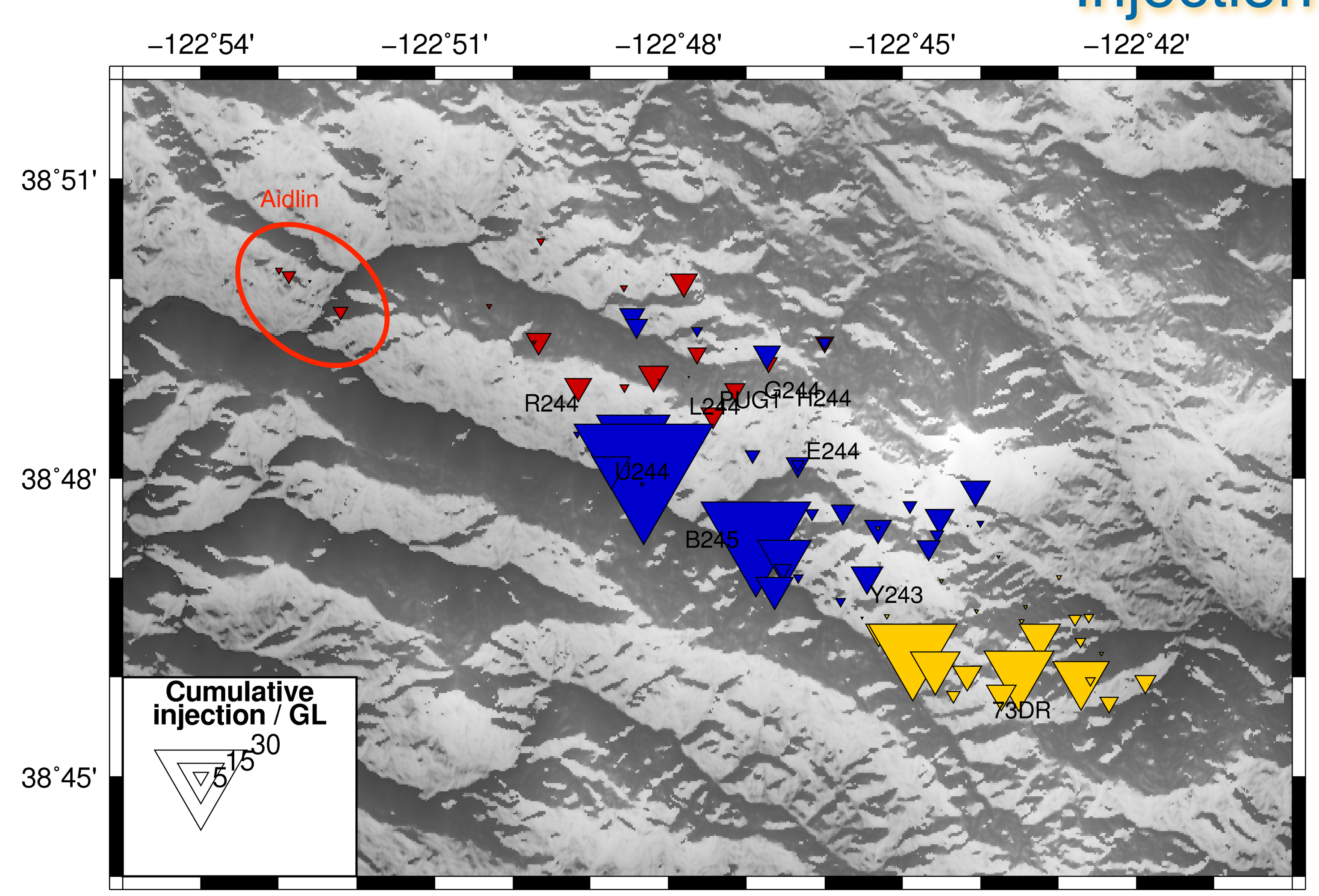


Figure 3 *Cumulative injection across The Geysers with respect to high quality GPS sites. Three zones of injection are assigned qualitatively based on location and use for the SEGEP and SRGRP projects (blue: central, sustained throughout; yellow: southern, increased with SEGEP; red: northern, increased with SGRGP).*

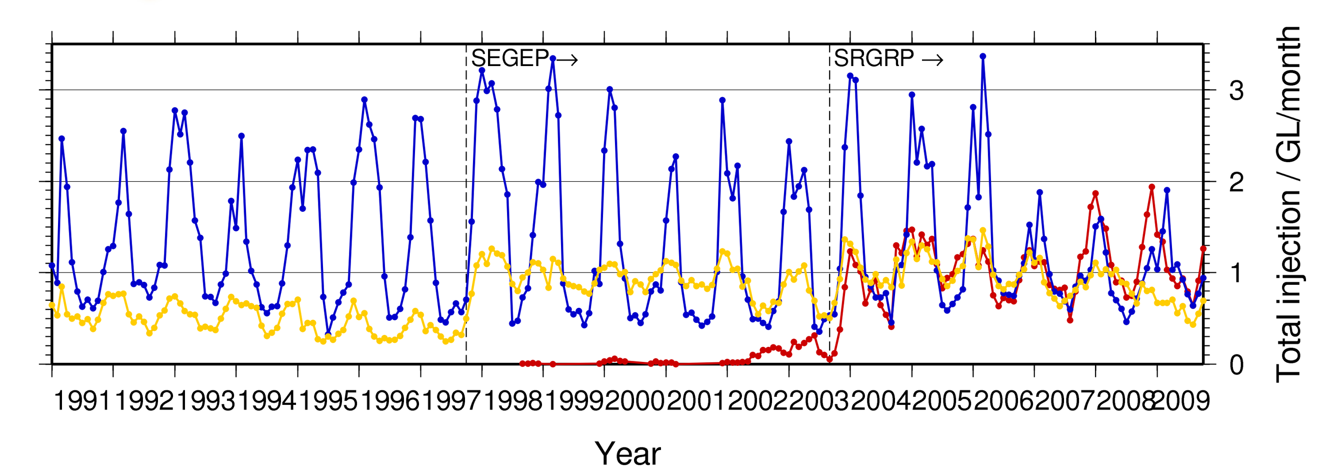


Figure 4 *Injection since 1991 for the three assigned zones (see Figure 3 and main text) to show likely reaction times at GPS sites. The South-East Geysers Effluent Pipeline (SEGEP) was opened in October 1997 followed by the Santa Rosa Geysers Recharge Pipeline (SRGRP) in September 2003.*

We focus on three areas of injection: a central zone (blue), which has sustained but fairly constant rates of injection throughout; a southern zone (yellow), which has a large and sustained increase in rate of injection from 1997/10; and a northern zone (red), which has a high rate of injection since 2003/10 only, excluding the Aidlin wells. Major primary injection wells are clearly visible as those with larger symbols. Sites such as E244, G244 and H244 do not require a two-velocity fit and appear to be unaffected by changes in injection. Sites such as 73DR and L244 show clear preference for a change in rate of subsidence around the introduction of SEGEP and SRGRP, respectively.

Time period comparisons

We directly compare the rates of subsidence over given periods, including and excluding the 2000 and 2001 data. We see a systematic decrease at a number of sites as these windows proceed in time.

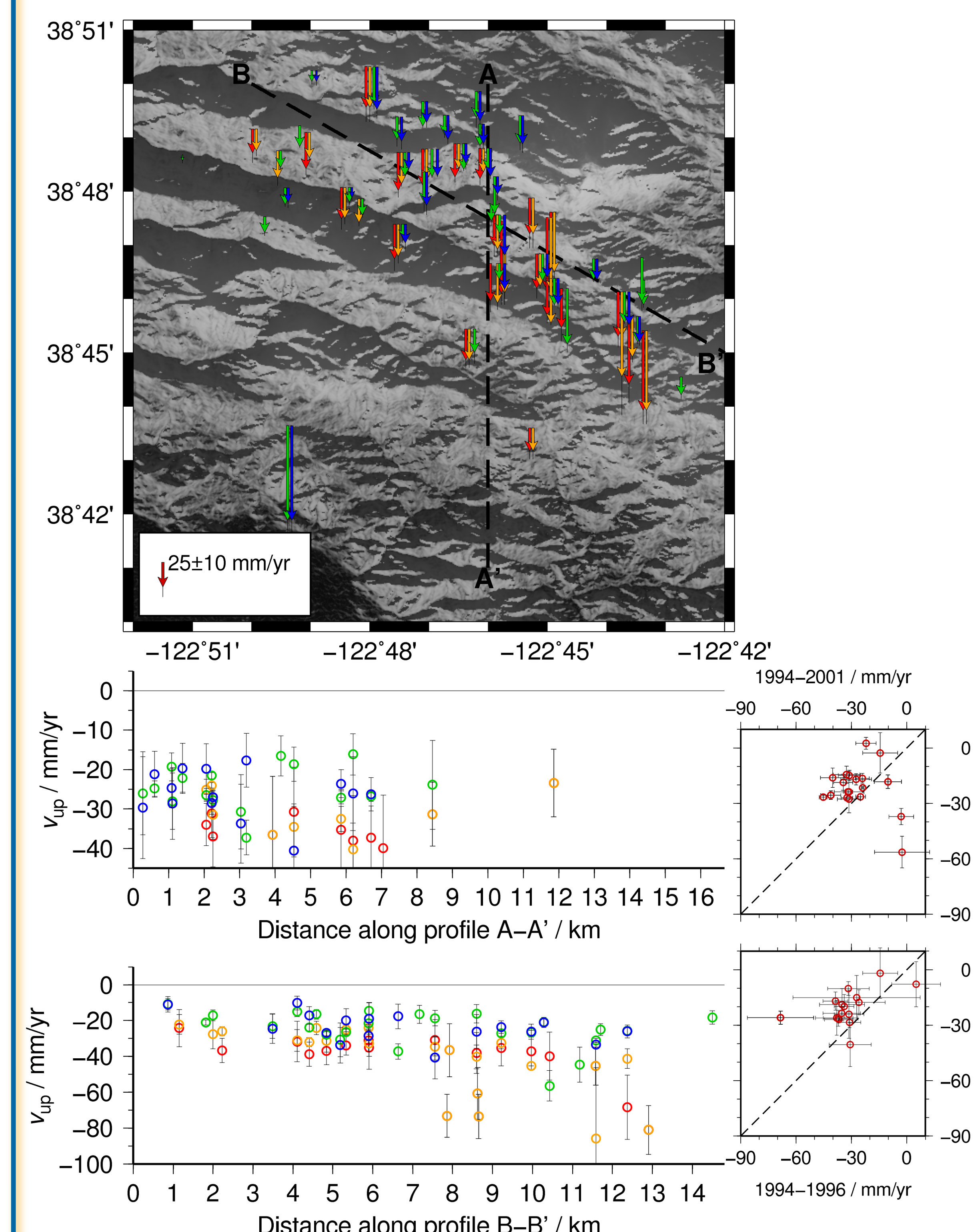


Figure 5 *Comparison of rates of subsidence over the periods 1994–1996 (red), 1994–2001 (orange), 2000–2010 (green) and 2006–2010 (blue). Top: map view; bottom, left: along profiles A-A' and B-B'; bottom, right: ratio plot of vertical velocities including (top) and excluding (bottom) the 2000 and 2001 data. Note some outliers disappear with the exclusion of the 2000 and 2001 data, indicating that these sites are heavily influenced by the low quality data.*

Conclusions

- A reduction in the rate of subsidence is measurable and statistically significant at sites throughout The Geysers.
- The reduction in the rate of subsidence appears a highly localised effect, constrained to around 1 km from the major sites of injection, which is consistent with the shallow depths at which water is injected.
- We continue to work on Mogi source modelling, with three-dimensional data, and on understanding the temporal and spatial relationship with injection sites.

References

Beall, J. J., et al. [2010], *GRC Transactions*, vol. 34, 47–52.
Mossop and Segall [1997], *Geophys. Res. Lett.*, *24*, 1839–1842.
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