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GRAVITY SIGNALS AT THE GEYSERS GEOTHERMAL SYSTEM

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ABSTRACT

Three high-precision gravity and GPS surveys have been conducted over The Geysers geothermal reservoir and surrounding area. These surveys, in September 2000, April 2001, and September 2001, provide an initial baseline for future imaging studies of spatial mass changes from the Santa Rosa Effluent Pipeline currently under construction. Analysis of the three surveys provides a measure of the seasonal and annual gravity and deformation signals currently occurring at The Geysers. GPS results show an average subsidence of 3±2 cm over the production field from September 2000 to April 2001, although some stations have significant deviations from this average. The deformation signal between September 2000 and September 2001 indicates an annual subsidence rate across the field of 2±2 cm/year. Gravity changes between April and September 2001 show an average of –38±8 μGal; a magnitude consistent with seasonal and annual production and ground water effects. Gravity change between April and September 2001 show an average change of –10±8 μGal. Spatial variation in the gravity changes may represent local injection and ground water responses.

INTRODUCTION

Repeated high-precision gravity measurements, coupled with simultaneous high-precision GPS data, can be used to investigate subsurface reservoir mass changes in an affordable fashion. Some examples of successful monitoring projects include Isherwood [1977], Allis and Hunt [1986], Pool and Eychaner [1995], and Sugihara [2001]. With the initiation of an enhanced injection program (the Santa Rosa Effluent Pipeline project) in mid-2002, repeated gravity and GPS have the potential to contribute to the understanding of the reservoir flow mechanics.

Starting in September 2000, repeated high-precision gravity and GPS surveys have been conducted at The Geysers geothermal reservoir and surrounding areas. Three surveys have been performed to date: September 2000, April 2001, and September 2001. Objectives of these surveys were to establish a comprehensive station network (Figure 1), to investigate existing seasonal and inter-annual variability over the region, and to provide the baseline for imaging the injection program.

DATA ACQUISITION & ANALYSIS

Gravity and GPS data are acquired using the techniques described in Allis et al [2000]. Briefly, gravity data are acquired using a Scintrex CG-3M gravity meter. At each station, data are acquired in 30 seconds samples for 12-15 minutes. These thirty 30 s time series are averaged to produce a single reading for each station occupation. Each station is occupied at least twice during a survey to provide instrument drift control. Surveys are referenced to a presumed stable reference frame of two or more regional gravity stations at least 8 km from the production field. Regional stations are chosen near ground water monitoring wells, allowing seasonal water table data to be correlated to changes in gravity.

Gravity data are corrected for solid Earth tides (using the formulation of Longman [1959]), elevation change (using the precision GPS data and a vertical gradient of -0.3086 mGal/m), and instrument drift. The instrument drift correction uses a combination of a linear long-term component and a discontinuous short-term function. Data from different days are tied through the use of a local base station near the reservoir.

GPS data are acquired at each gravity station using a Trimble 4700 GPS system, in a rapid-static post-processed differential mode. A local base station (H1244) with excellent sky view has been established on the Geysers production field, which minimizes baseline lengths. Typical baseline lengths are 13 km or less, with only a handful of stations having baselines of over 15 km. H1244 is tied each survey to the Hopland, CA regional continuous station using data available from NOAA. The local base station is run each day of the survey for at least 8 hours; typical surveys have at least 10 recording days. Rover occupations are for a minimum of 30 minutes, with a 15 second sample interval. Unfortunately, not all gravity stations have sufficient sky view for useful GPS measurements.

GPS data are analyzed using Trimble Geomatics Office software. The baselines from H1244 to Hopland are analyzed first, to determine the precise position of the base station. Once the coordinates of H1244 are computed, they are fixed, and the remainder of the network baselines computed. Geomatics Office allows the use of both Hopland and H1244 to construct two baselines to each station, which are not independent. These are analyzed simultaneously. An elevation correction is only applied to stations with an accurate baseline solution; baselines which do not provide an accurate solution are discarded.

To test the precision of the GPS system and analysis method, a trial was conducted in September 2001 where the station JIMTOWN (baseline length of 13 km) was occupied twice as independent stations on two different days, at different times of the day (one morning occupation, one late afternoon). These two occupations were reduced independently, and the resulting positions compared. Differences were (0.5, 1.6, 0.3) cm in (x, y, z) coordinates. These differences are mostly within the vertical error bound of ±1.3 cm predicted by theory [Hofmann-Wellenhof et al, 1993]. Therefore, GPS position errors are taken as ±2 cm vertically.

The current station network contains 160 stations in the production field area, including five regional control stations (Figure 1). On the main production field, station spacing is nominally 1 km, although a completely regular grid is precluded by the terrain. There are two profiles that extend out from the production field with ~1 km spacing, to help image the actual flow front boundaries in the north and south ends of the field. The existing network was installed in September 2001; previous surveys used a subset of 60 stations concentrated on the field, but include at least four of the five regional stations in the current network.

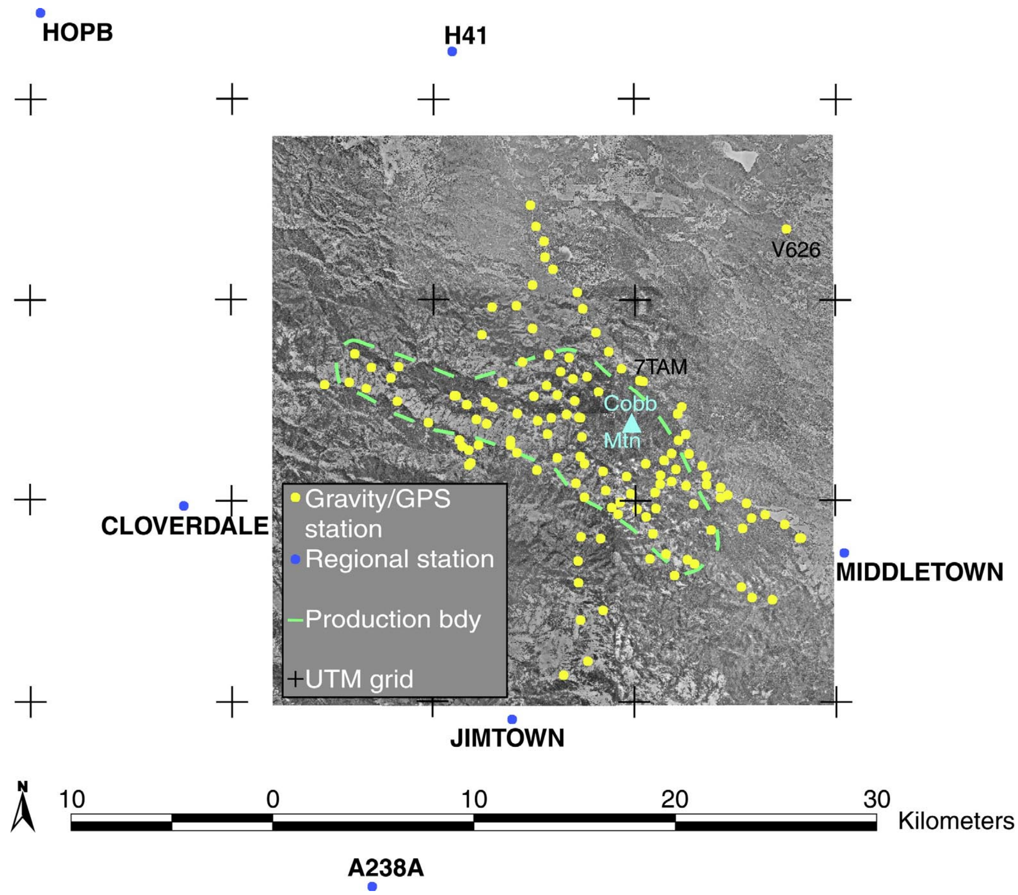

Figure 1. Station network at The Geysers. The dashed green line marks the approximate boundary of the production field. Cobb Mountain is labeled for reference in Figures 2-5.

RESULTS

The three surveys allow gravity and elevation changes between September 2000–September 2001, September 2000–April 2001, and April 2001–September 2001 to be computed. Elevation changes between September 2000 to April 2001 and April 2001 to September 2001 are shown in Figures 2 and 3. Gravity changes, in μGal, are shown in Figures 4 and 5. These changes have been corrected for elevation change (where the data exist), and referenced to a presumed stable reference frame. Where elevation change data are lacking, no elevation correction has been applied in this interpretation.

Due to a meter failure on the final day of the September 2000 survey, the regional station gravity data are not reliable. Therefore, gravity differences between September 2000 and April 2001 are referenced to the station 7TAM, which is slightly off the field. Differences between April and September 2001 are referenced to the average of CLOVERDALE, JIMTOWN, and MIDDLETOWN; regional station H41 is used as a check of the reference frame.

Water table data are available for wells near two regional stations (JIMTOWN & H41), and near a single gravity station (ABSG) on the production field. Water levels are measured twice yearly in the regional well near H41, by the California Department of Water Resources. Water levels are measured simultaneously when GPS and gravity data are collected at the JIMTOWN and ABSG stations. Using September 2000 as a reference, the seasonal variations in the local ground water aquifers can be observed. The water level changes for the three monitored wells are shown in Table 1.

Table 1. Water level changes; positive change implies rise towards the ground surface

Station	**ΔZ(m)** Sep 2000 to Apr 2001	**ΔZ(m)** Sep 2000 to Sep 2001
ABSG	1.78	-0.77
JIMTOWN	1.83	-0.27
H41	0.61	-2.22

The change in gravity due to ground water level changes can be modeled as a Bouguer slab. The predicted gravity changes, assuming a porosity of 20% (and saturation change of 100%), are shown in Table 2.

Table 2. Predicted gravity changes due to ground water change; 20% porosity, 100% saturation change assumed.

Station	**Δg(μGal)** Sep 2000 to Ap 2001	**Δg(μGal)** Sep 2000 to Sep 2001
ABSG	14	-6
JIMTOWN	15	-2
H41	5	-18

DISCUSSION & CONCLUSIONS

GPS Data

Elevation changes between September 2000 and April 2001 are significantly larger than the 2 cm assumed error; in the center of the production field, stations show an average subsidence of 3±2 cm, with a range of 1 to 8 cm. The average subsidence rate of 4.5 cm/yr is not significantly different from the average rate (4 cm/yr) found by previous subsidence surveys [Lofgren, 1981; Mossop et al, 1997] for the time periods of 1973-1977 and 1977-1996 respectively.

Elevation changes between April and September 2001 (Figure 3) show less subsidence than the previous 8 month data (Figure 2); the average subsidence in the center of the field is 1±2 cm, which is not significant. Some stations do show significant changes; these may represent local reservoir effects; more data is required to determine if the signal is real.

A total of 6 stations have been removed from the plotted GPS data due to processing problems; the analysis algorithm could not find an atmospherically corrected baseline solution for at least one survey, and hence no precise position changes can be computed. These five stations include four of the regional stations: CLOVERDALE, A238A, H41, and MIDDLETOWN. The remaining regional station, JIMTOWN, has good positions in April and September 2001, so gravity change at this station is only corrected for subsidence between April and September (2 cm).

With subsidence of typically 1-3 cm, the gravity effect is small, 3-9 μGal. Therefore, it is unlikely that computed gravity changes at stations without precise positioning are due primarily to uncorrected elevation changes.

Gravity Data

During the September 2000 survey, the gravimeter sensor failed partway through the measurements of the regional stations. Thus, all regional stations have suspect data from the September 2000 campaign, and are not suitable for use in a reference frame. Instead, for the gravity changes between September 2000 and

April and September 2001, station 7TAM has been used as the reference frame.

Table 3. Gravity changes at regional stations, assuming the average of CLOVERDALE, JIMTOWN and MIDDLETOWN stable.

STATION	**Δg(μGal)** Sep 2000 to Apr 2001	**Δg(μGal)** Apr 2001 to Sep 2001	**Δg(μGal)** Sep 2000 to Sep 2001
CLOVE*	-11±19	-2±16	-12±16
JIM**	11±24	1±12	13±12
H41	-96±17	-20±15	-115±15
MID***	N/A	2±8	N/A

* CLOVERDALE
** JIMTOWN
*** MIDDLETOWN

Despite being referenced to a near-field station, the gravity changes between September 2000 and April 2001 show spatial clustering, with magnitudes that are reasonable (Figure 4). Production records (Figure 6) for the Geysers indicate a cumulative net mass loss of 20.55 Mt for this period. Using a 1-D Bouguer slab approximation (Allis et al, 2001), with an assumed reservoir area of 40 km^2, predicts an average change across the field of –20 μGal. Ground water changes at the regional and ABSG wells show changes of ~1.8 m, which is equivalent to a gravity effect of +14 μGal (Table 2). Due to the low porosity of the reservoir cap rocks and the relatively shallow sediment cover, it is unlikely that ground water changes are uniform across the reservoir and regional stations. Hence, a groundwater increase at the reference station 7TAM could be mistaken for an increased gravity decline in the reservoir stations. Hence, net mass change and ground water effects could explain up to –34 μGal of change. The average change across the field is –38±8 μGal.

Much of the variability in the data seen in Figure 4 may be explained by reducing the amount of injection or production present at a given station. If a station were only affected by production, it would be equivalent to a net mass loss of –40 Mt, or –40 μGal. A station with only injection effects would show a gravity change of +20 μGal. Hence, variations in ground water and production signals can potentially give rise to variability between –60 and +20 μGal.

The spatial variation seen in Figure 4 is coherent; gravity changes tend to occur in clusters. This spatial coherence increases confidence in the gravity changes; it is unlikely such a coherent signal would arise from random instrument noise.

Figure 5 shows gravity differences between April and September 2001. Regional stations CLOVERDALE, MIDDLETOWN, and JIMTOWN have been used to construct the reference frame; gravity change at H41 is used as a check of the other reference stations. Regional station gravity changes are shown in Table 3. Note the relatively small magnitudes (average of –10 μGal) over the production field. Again, using the 1-D Bouguer slab formula, the reservoir net mass loss of 12.31 Mt during this period predicts a gravity change of –12 μGal. Ground water changes predict gravity effects of up to –20 μGal (Table 2). In the case of regional station H41, up to -23 μGal of gravity change can be attributed to ground water change. This accounts for the -20 μGal change observed at the station. However, the large ground water signal at H41 implies that the stations JIMTOWN, CLOVERDALE, and MIDDLETOWN have little gravity effect from regional ground water; this would most likely be due to low porosity at these stations.

Spatial coherence, in both Figures 4 and 5, increase confidence that the gravity changes are tracking real signals. Clusters showing increased gravity may be indicating areas of recharge from injection. Several stations show no significant change, which may indicate the absence of significant ground water and reservoir change at that location. Detailed production and injection data, in combination with improved modeling efforts, are needed to investigate these possibilities.

The changes in both subsidence and gravity decline rate between April and September 2001 may be a response to California power problems in late 2000. The exceptionally high production rates in late 2000 (Figure 6), with a net mass loss of 20.55 Mt, may have caused significantly faster gravity decline than the typical long-term rate; an average rate of –57 μGal/year compared to the long term average of ~-30 μGal/year (Allis et al, 2001). Surface deformation possibly also responded to this production high, showing an average subsidence of 3 cm (4.5 cm/yr). Once the power crisis passed, production was reduced and injection increased to reduce net mass loss to 12.31 Mt, resulting in a slower gravity decline (-20 μGal/year) and relatively static surface between April and September 2001.

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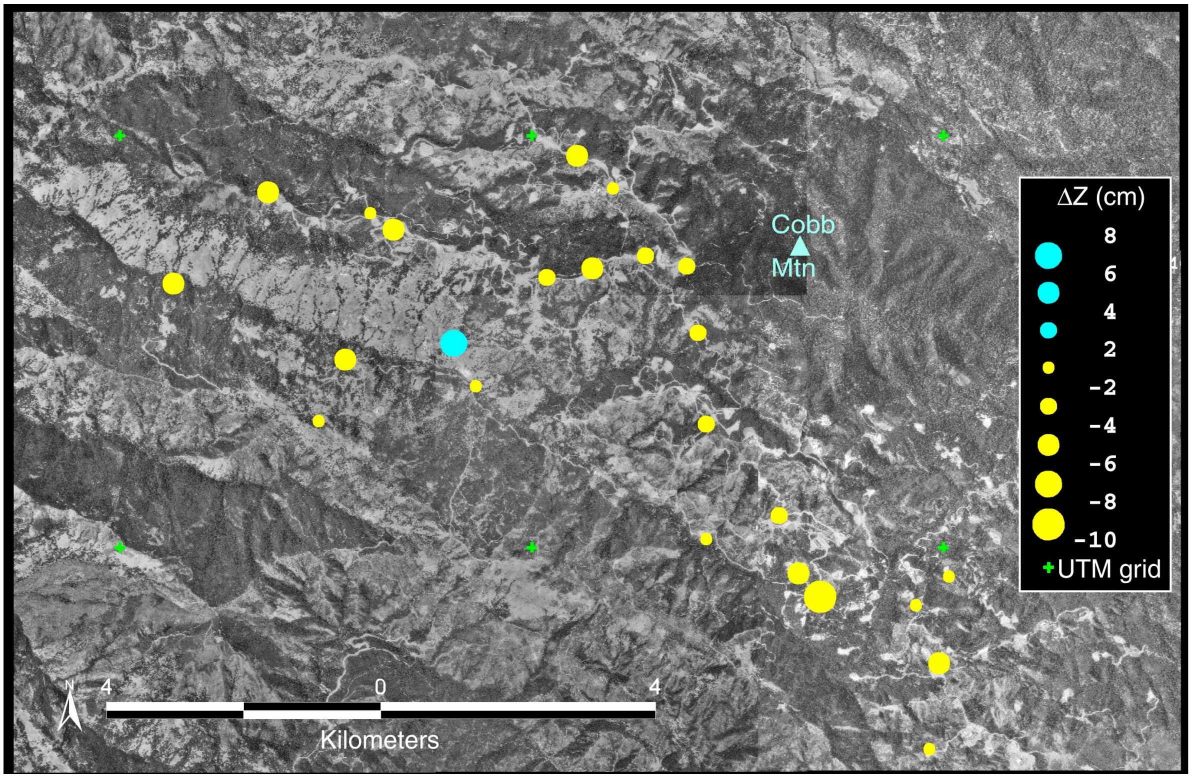

Figure 2. Elevation changes from September 2000 to April 2001; CLOVERDALE shows 6 cm of elevation change, but is omitted for clarity. Errors are taken as ±2 cm.

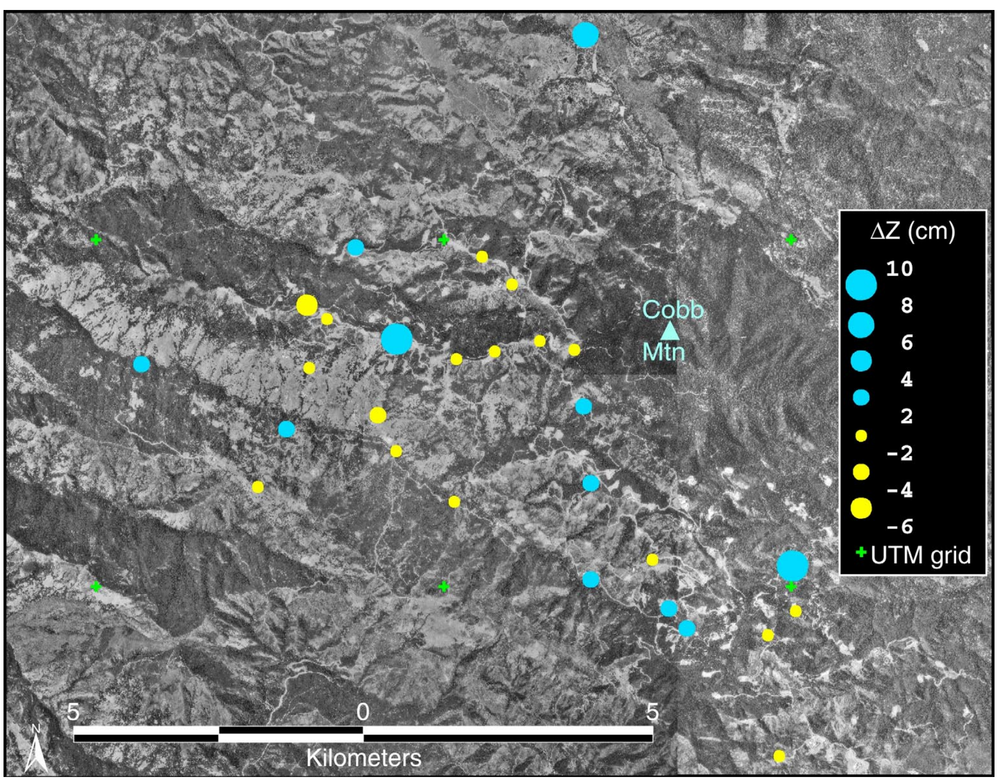

Figure 3. Elevation changes from April 2001 to September 2001. Errors are ±2 cm.

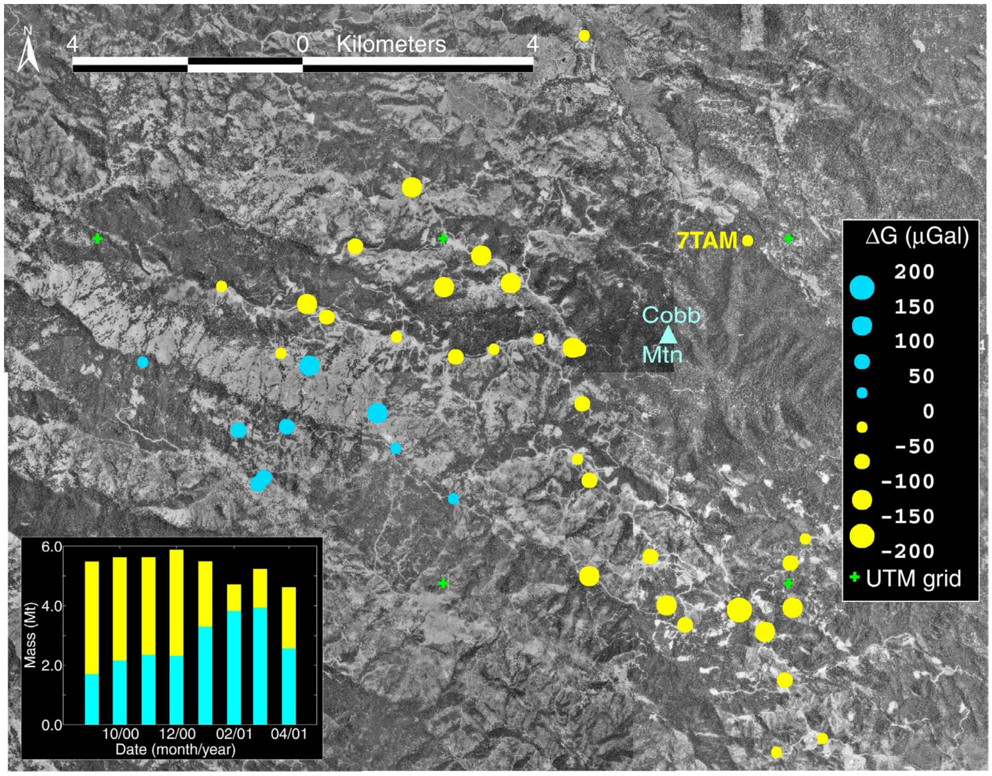

Figure 4. Free-air corrected gravity changes from September 2000 to April 2001. Stations are referenced to 7TAM. Inset shows production history (yellow is extraction, blue is injection) for the same period.

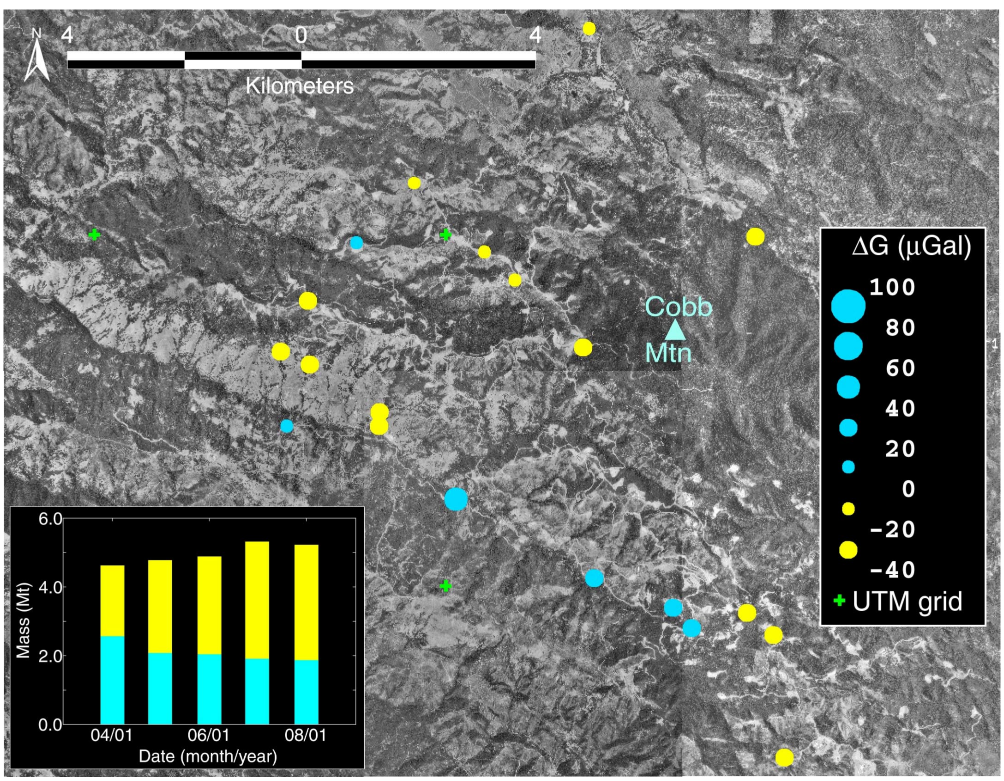

Figure 5. Free-air corrected gravity changes from April 2001 to September 2001. Stations are referenced to the average of CLOVERDALE, JIMTOWN, and MIDDLETOWN. Inset shows production history (yellow is extraction, blue is injection) for the same period.

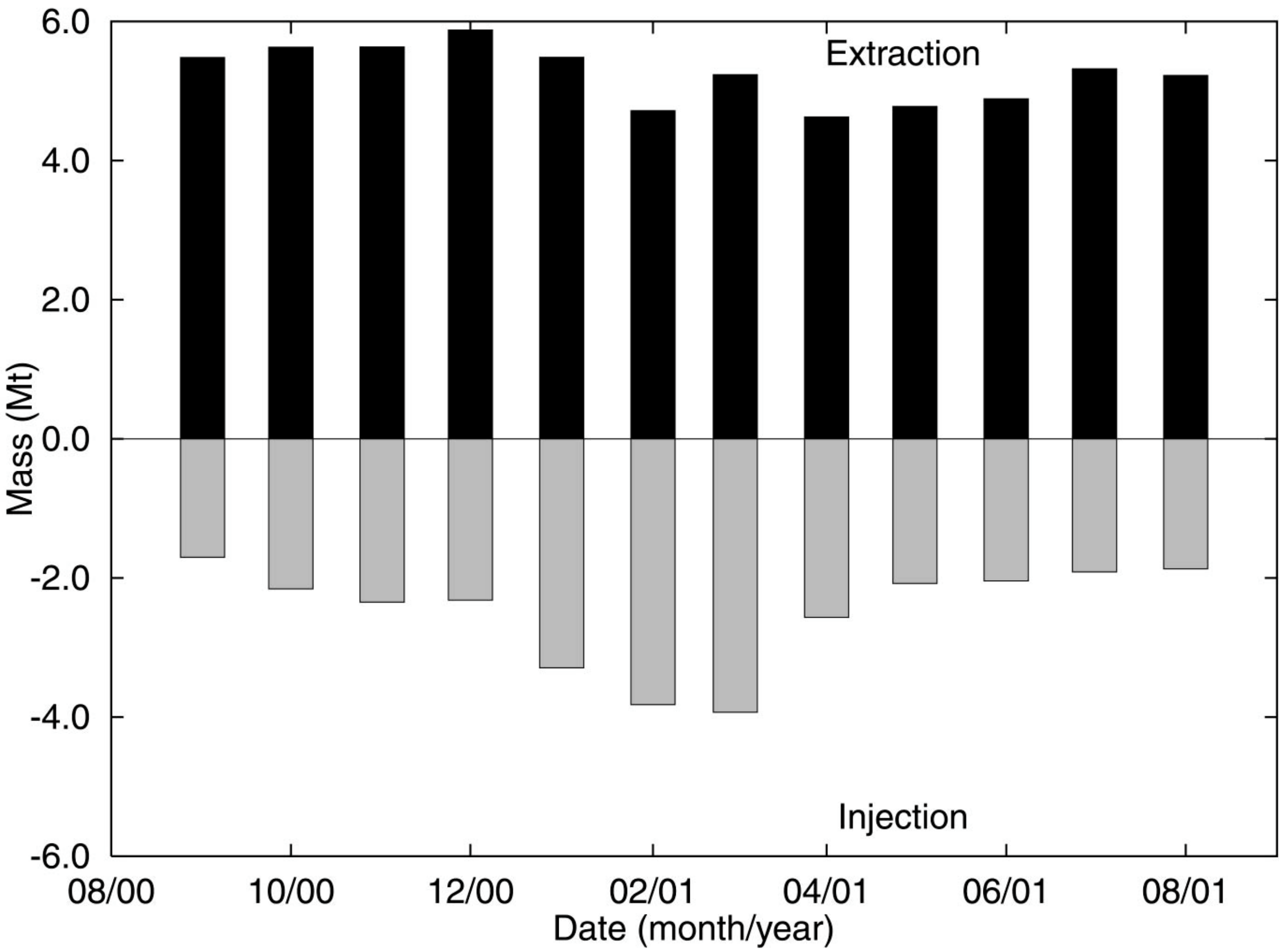

Figure 6. Mass extraction history at The Geysers, September 2000 to August 2001. Bars are monthly totals, in millions of metric tons ($1x10^9$ kg). Negative mass is injection, positive mass is extraction.