4-D Gravity at The Geysers

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ABSTRACT

Five high-precision gravity and GPS campaigns have been completed on The Geysers geothermal field between 2000 and 2011. Gravity changes for 4 campaigns between 2000 and 2006 are very consistent with aggregate production and injection mass totals, after correction for GPS-derived elevation changes and near-surface groundwater changes. Average change across the field varies from -86 μGal for April 2001-September 2000 to -6 μGal for September 2001-April 2001. Gravity change from 2006 to 2011 is 97 μGal higher than expected from reported production and injection totals to December 2010 and known groundwater changes in wells in the valleys around the production field. Detailed production and injection data are expected to become available for the monitoring period, which will be used to update and validate a reservoir model based on well temperature and pressure constraints.

Introduction

Repeated high-precision gravity measurements can be used to track mass changes of engineering interest, for example groundwater or steam-field changes [*Pool and Eychaner,* 1995; *Gettings et al.*, 2002; *Sugihara and Ishido*, 2008]. Gravity change is sensitive to elevation and mass changes in the reservoir and cap; when coupled with GPS measurements to determine surface deformation, the gravity changes can be corrected to reflect only the mass changes under a station. Thus, gravity and GPS monitoring can provide insight into saturation, temperature (via thermal contraction), mass balance, and steam-field boundary changes over time. While these changes can be detected in other ways (e.g. production well monitoring, microseismic networks, or InSAR), gravity monitoring can play a crucial role in projects with challenging access, large spatial extent, or deep sources. At The Geysers geothermal system in northern California, all three difficulties are present. Despite being the largest produced geothermal system in the world, The Geysers does not have a particularly well-defined boundary for the overall system. Multiple operators and a long production history combine to make delineation of the maximum extent of production changes, reservoir boundaries, and well interference difficult at best. To help address the challenges of where and how The Geysers reservoir is changing at depth and on the surface, gravity and GPS monitoring began in fall 2000.

In this paper, we present initial interpretations of the gravity and GPS monitoring campaigns from 2000 to 2011. As more production and injection data, groundwater levels, and more refined GPS solutionsbecome available, our interpretations will subsequently be updated. The data available currently are sufficient for a first look at the gravity changes, but detailed analysis will require the well-by-well production and injection data.

Station Network

Data collection started in September 2000 with an initial network of 50 gravity stations on the main production field and off-field valleys. We attempted to use stations from the 1970s precision gravity campaigns [*Isherwood*, 1977] wherever possible; however, construction and weathering made recovery of most benchmarks from those early campaigns impossible. Subsequent campaigns extended the network to 58 stations in April 2001, 108 stations in September 2001, and 120 stations in 2006 and 2011. However, due to loss of stations between campaigns, we have actually occupied 166 sites total over 5 campaigns, but only 120 remain viable in the 2006 and 2011 surveys.

Various stations were lost due to road construction and other factors, so absolute station count does not necessarily reflect that only 2 stations were lost over the 5 campaigns. Over the entire monitoring period, 46 stations have been lost or abandoned in the production field and surrounding region. Most were lost due to construction (e.g. road widening, hill sculpting, sidewalk replacement), but 10 have been abandoned because the station could not be relocated or the abandoned station replicated a nearby, better station.

The full station network, shown in figure 1, extends across the current production zone of the The Geysers, with a nominal spacing of 1 km. We have also established some stations extending from the production field to the surrounding valleys; one line from the SE corner extends to the SW, one line extends to the SE, and a line of stations extends to the NE from the northern edge of the field.

A sparse ring of stations on the NE edge of the current production will capture upcoming production-induced changes in the newly explored high-temperature reservoir.

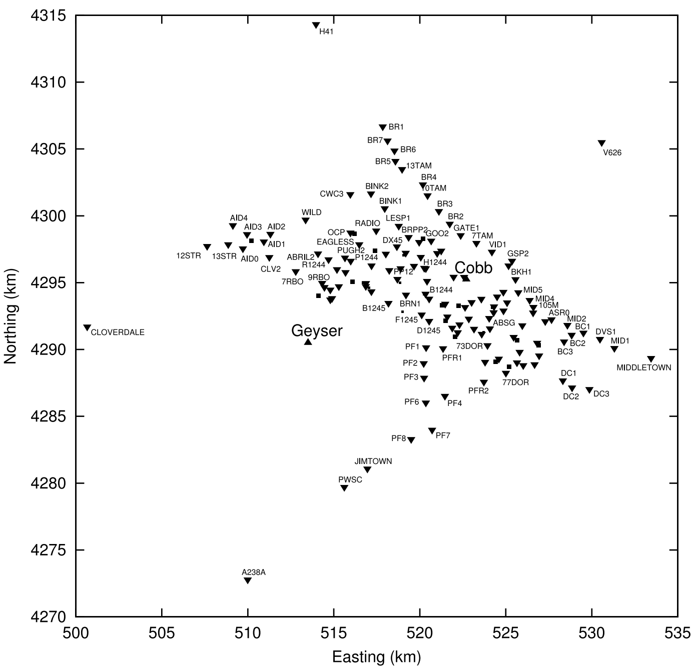

Figure 1. Station network at The Geysers. Gravity stations are shown as downward-pointing triangles, power plants as squares, and mountain peaks as upward-pointing triangles. All stations are named, but many on the production field are omitted for clarity. Power plants and peaks form a convenient reference frame for interpreting gravity change maps.

To help remove instrument drift and investigate seasonal signals at the reservoir, six regional stations in the valleys around The Geysers are measured each campaign. Stations H41 (Kelseyville, CA), Cloverdale, A238A (Healdsburg, CA), Jimtown, V626, and Middletown fully surround the production field, but are at least 1000 m lower in elevation than the stations on the field. This elevation difference precludes fully capturing the precipitation-caused gravity changes on the field, as the precipitation on the field is noticeably different than in the surrounding valleys.

Data Collection

Measurement techniques able to achieve precision and accuracy of 5 μGal have been developed over the past few decades, taking advantage of recording gravimeters and time-series analysis; for the campaigns presented here the data are collected and processed according to *Gettings et al.*[2008]. Campaigns from 2000 to 2006 used a Scintrex CG-3 gravimeter; the 2011 campaign used a CG-5 gravimeter. Gravity change precision varies between 3 and 7 μGal for all stations in all campaigns.

Gravity measurements were conducted on all stations on each campaign, along with high-precision GPS. Campaigns in 2000 and 2001 used GPS occupations of 30 and 60 minutes in a rapid-static mode. A continuous local GPS base was established at H1244 for the 2000 and 2001 campaigns, with precise coordinates computed from all the data on H1244 referenced to the continuous station HOPB in Hopland, CA. Precise H1244 coordinates were used to compute precise coordinates for all campaign stations, with estimated accuracy of 3 cm vertical. Starting in 2006, GPS data were collected for a minimum of 8 hours, using NGS continuous reference stations (CORS) for post-processing. Vertical accuracy is estimated at better than 1 cm for 2006 and 2011 positions.

Gravity Changes from 2000 to 2011

Corrected gravity changes are presented in figure 2, in μGal, for each campaign compared to the immediately preceeding one. Changes have been corrected for instrument drift, elevation change, and estimated near-surface water changes.

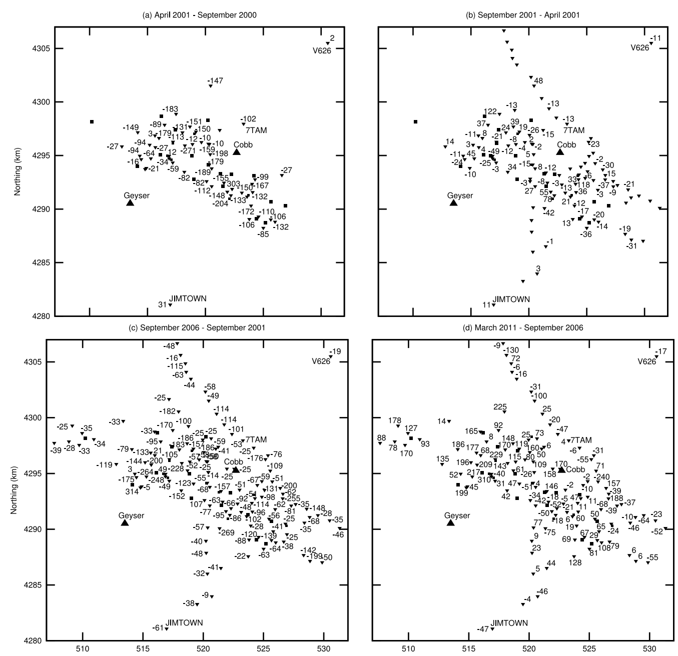

Figure 2. Gravity changes, in uGal, between campaigns. Stations are marked with downward-pointing triangles with gravity change shown next to the marker. Power plants are shown as squares, and mountains as upward-pointing triangles. See figure 1 for station names. Gravity changes corrected by -25 (2006) and -80 (2011) μGal for estimated groundwater effects (see text for details).

Instrument drift is removed during campaigns by a daily drift function built from repeated occupations, as detailed in *Gettings at al.*[2008], and between campaigns by updating gravity changes such that the average change of stations Cloverdale, H41, and Jimtown is zero. Holding the average of stations at zero change also removes a groundwater signal, although not the exact signal on the production field. Without well level measurements across the production field, it is not possible to accurately predict the groundwater-caused gravity changes, so some residual groundwater signal will be present in gravity changes on the field.

Gravity changes by -308.6 μGal/m of vertical change; we use the GPS results to determine vertical change at each station, and then compute a gravity correction from the free-air gradient. Elevation changes from GPS results are shown in figure 3. Differences are shown in mm; stations without changes shown are uncorrected due to a lack of data during a particular campaign. Note the changes between campaigns, which are consistent with observable surface cracks on roads and hills across the production field and surrounding region. Since GPS measurements yield differences at the surface, elevation changes are a combination of near-surface motion due to landslide, water, etc. as well as pressure and temperature changes in the deep reservoir from production and injection. Separating the near-surface and deep deformation signals is not trivial, and work is ongoing.

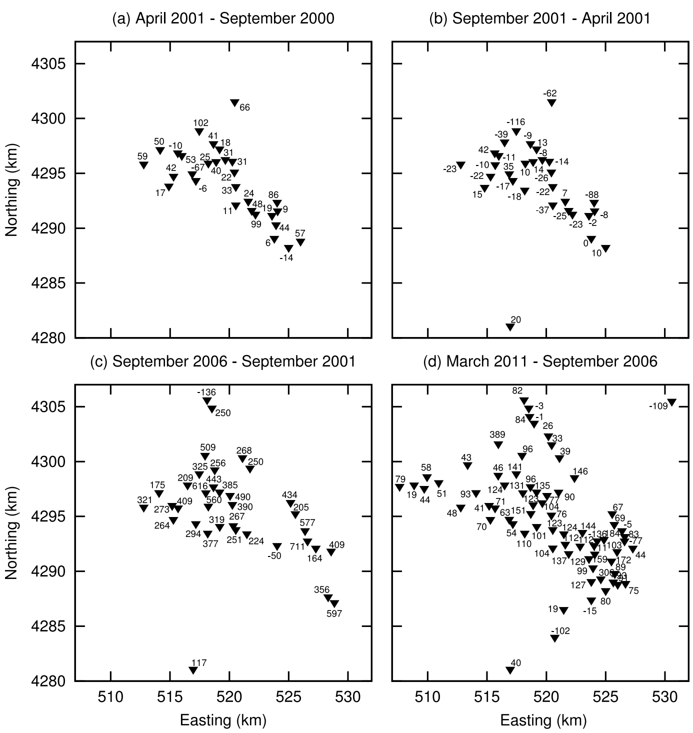

Figure 3. Elevation change, in mm, between campaigns. Elevation changes are measured via GPS positions on the surface, and thus represent changes in the near-surface and deep reservoir. Gravity measurements are corrected for elevation change assuming the standard free-air gradient of -308.6 μGal/m.

Water table elevation changes for wells near Jimtown, Cloverdale, Middletown, and H41 are shown in figure 4, converted to a gravity change relative to October 2000. Changes in water table elevation can be converted to an estimated gravity change by assuming a porosity (0.25) and that water table changes act as an infinite slab; the gravity change is then 10~μGal/m of water level change. Jimtown has the largest changes, ranging from -20 to +80 μGal . Kelseyville wells (near H41) show the second largest changes (up to +60 μGal), but with much less variability after 2002. Cloverdale (and Healdsburg) wells show small gravity changes (-10 to +10 μGal), due to very stable water levels. Both Cloverdale and Healdsburg are in the valley bottom, near the Russian River, so water levels are expected to be fairly stable even with some pumping. Note the variability in water levels, and hence estimated gravity effects, for Jimtown and Kelseyville despite the wells being within miles of one another. Given the variability and size of water level changes, it is possible for a groundwater signal on the production field to exceed 80 μGal peak-to-trough between the dry part of the year (September/October) and the wet (March-May). Jimtown is near a canyon mouth and next to a large stream; the station will have gravity effects from stream-stage changes, and the estimated gravity effects are thus a lower bound on gravity signals at Jimtown.

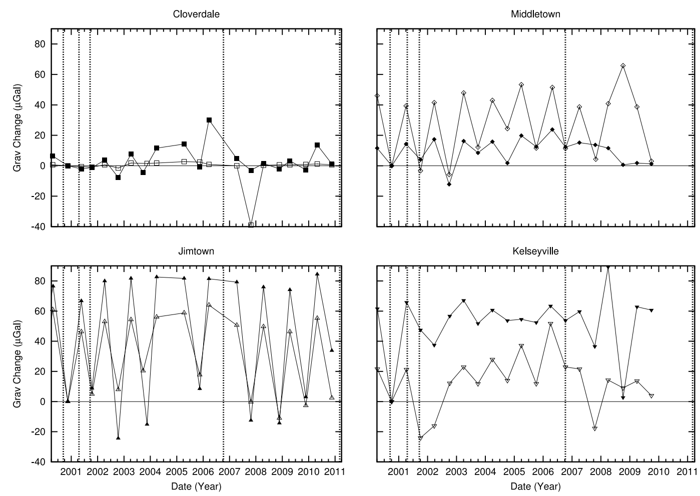

Figure 4. Water table elevation changes from October 2000, converted to gravity changes using an infinite slab assumption with 0.25 porosity. Vertical dotted lines show dates of gravity campaigns. Wells are chosen as being the closest available with data covering the monitoring period. Wells are a mixture of irrigation, domestic, and unused. All data are from the California Department of Water Resources website (http://www.water.ca.gov).

Gravity changes from April 2001 to September 2000 are generally negative, with large decreases in the northern and southern production zones. Net mass loss over the entire field during September 2000 to April 2001 is 20.55 Mt (20.55×10^9 kg); all production and injection data are taken from the California Division of Oil, Gas, and Geothermal Resources website (http://www.conservation.ca.gov/dog/Pages). Using an infinite slab formula for a reservoir with an assumed area of 40 km^2 [*Allis et al.*, 2001], 20.55 Mt of production equals an average gravity change of -21 μGal across the field. Without detailed production and injection data, which are currently unavailable, only bounds of gravity effects can be calculated for stations on the field. Production mass loss from September 2000 to April 2001 was 42.68 Mt, with 22.13 Mt of injection. If all mass change occurred at a single station, at the depth of the bottom of the well casing (1250 m), the station should see a gravity change of -186 and +95 μGal for production or injection respectively. Thus, gravity changes on the order of -100 μGal can be easily attributed to local production. Stations with near-zero and positive gravity changes are believed to reflect local conditions where injection dominates production.

Gravity changes from September 2001 to April 2001 are much smaller, in keeping with a production mass loss of 20.21 Mt and injection gain of 7.90 Mt; predicted gravity changes range from +34 μGal for pure injection at a point to -86 μGal for pure production, with a reservoir-wide average predicted of -12 μGal; the average of all repeated stations is -6 μGal, indicating a 6 μGal difference, barely beyond the measurement error bounds of 5 μGal. Most gravity change is again clustered around the production areas. The large number of stations with zero gravity change are stations newly occupied in September 2001. Groundwater-induced gravity change should be negative due to summer drought, and could add tens of μGal to the production signals. Most stations are slightly negative, although the positive cluster in the NW of the field may be injection and local groundwater signals. Once detailed, well-by-well injection and extraction data are available, more detailed interpretations of the gravity changes can be made.

Differences between the 2006 and September 2001 surveys are shown in figure 2c. Cumulative extraction and injection masses between 2001 and 2006 are 313.16 Mt and 217.89 Mt, respectively. Estimated maximum gravity signals from production and injection are -1337 μGal and +930 μGal; a field-wide average for the difference between extraction and injection is -95 μGal. To help account for groundwater change between 2001 and 2006, -25 μGal has been added to all stations; inspection of gravity changes at stations off the production field but nearby, with the reference stations held at zero, found a typical drop of 26 μGal between 2006 and 2001. Although a suitable groundwater change is not seen at the Cloverdale and Healdsburg wells to account for a 26 μGal shift, changes at Jimtown and Kelseyville wells could easily give a 26 μGal signal due to groundwater drop. Average gravity change across the field is -73 μGal, 22 μGal higher than predicted. Whether this difference from field-wide predicted is due to temporal and spatial sampling, incomplete groundwater-effect removal, or local production and injection details remains to be investigated with detailed mass flow data.

Between 2011 and 2006, gravity changes on the production field are convolved with significant groundwater-induced changes due to seasonal differences; Jimtown and Kelseyville well changes imply that seasonal groundwater changes could produce gravity signals of 80+ μGal at stations. Since the 2011 campaign was conducted in February and March 2011, compared to the September/October campaign of 2006, a uniform shift of -80 μGal has been applied to all stations in 2011 to remove much of the seasonal groundwater signal. Production data is only available to December 2010 currently, so predicted gravity changes from production and injection are lower bounds. Extraction and injection between December 2010 and September 2006 were 254.90 Mt and 196.48 Mt, respectively. These mass totals predict maximum gravity changes of -1089 and +839 μGal, with a field-wide average of -58 μGal. Average gravity change across all stations is 39 μGal. The 97 μGal difference between average measured change and predicted average change is currently unattributed. Claiming all the difference is due to groundwater effect indicates a seasonal signal of 170-180 μGal, which seems unlikely based on well changes in the valleys around the field. *Goodkind* [1986] found changes of such magnitude, which was attributed to seasonal changes of a single year, rather than 5 years of groundwater change in addition to the seasonal signal (March 2011 versus October 2006). It is thus possible that a better groundwater effect estimate could be 180 μGal; additional water well information on the production field would be extremely helpful in deconvolving geothermal reservoir gravity signals from the near-surface groundwater signals, although such data are not currently available to the authors.

Discussion and Conclusions

Ten years of gravity changes between 2001 and 2011 show generally good agreement with predicted bounds from production and injection data. In particular, 2001 campaigns are in good agreement with changes of appropriate magnitude, sign, and location for the production areas. Changes in 2006 are more varied and will need well-by-well reservoir data to determine how well gravity changes match the known mass changes and depths. The mismatch in measured versus predicted changes between 2011 and 2006 may well be due to underestimates of the groundwater effects on the production field or high injection during early 2011 just before the gravity campaign; an ongoing search for groundwater levels somewhere on the production field, and additional production data, should allow partitioning of the difference between predicted and observed gravity changes.

Currently, only aggregate production data are available on a monthly basis, preventing detailed interpretation of gravity changes between campaigns for individual portions of the monitoring network.

Well-by-well data for September 2000 to April 2011 would allow such detailed interpretation; such data are being prepared by the operators for use in gravity interpretation, but are not yet available to the authors. Additionally, well temperature and pressure data may become available, which will allow incorporation of all geophysical data in a reservoir simulator that spans the production field and surroundings.

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