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PRECISION GRAVITY CHANGES AT THE GEYSERS GEOTHERMAL RESERVOIR, 1975 – 2000

R.G. Allis[1], P. Gettings[2], W.F. Isherwood[3] and D.S.Chapman[2]
[1] Utah Geological Survey
[2] Dept. of Geology and Geophysics, University of Utah
[3] Lawrence Livermore Laboratories

ABSTRACT

During two field trips to The Geysers reservoir in July and September 2000, precision gravity and GPS measurements were made at 32 benchmarks previously occupied between 1975 and 1979. Comparisons with the late-1970s measurements indicate gravity changes of between +60 and –440 μGal. When corrections are made for the gravity effect of ground movement based on the elevation measurements of Mossop et al. (1997), the resultant gravity changes attributable to subsurface mass changes range between –100 and –700 μGal. The greatest gravity decreases are in the central Geysers region between Units 14 and 18-13. The southwestern limit of this area is not delineated by these measurements. Assuming most of the mass to have been withdrawn from a reservoir thickness of about 1 km, these changes imply the mass loss to have occurred due to dry-out of trapped water with an equivalent 2% pore volume (i.e. original undisturbed liquid-saturated porosity was 0.02). In the old production area (Units 1 – 8), the gravity change since 1974 is only about –450 μGal. However consideration of the net mass extracted from the early steam field prior to the first precision gravity measurements in 1974 suggests that a gravity decrease of around 200 μGal had probably already occurred in this area. There has also been significant injection in this area. An additional 30 new benchmarks have been established during the 2000 surveys to enable observation of the amplitude of seasonal gravity during 2001. The new network will then be expanded to around 150 benchmarks to allow annual precision gravity and elevation monitoring to help delineate future saturation changes in the reservoir as a result of an enhanced injection program planned for The Geysers.

INTRODUCTION

Two precision gravity surveys were carried out at The Geysers, northern California, during 2000. These are the first of several that will be made over the next three years as part of a DOE-funded initiative to establish the value of combined modern precision gravimetry and precision GPS field campaigns to monitoring the reservoir response to enhanced cold water injection. The technologies of both precision gravimetry and GPS instrumentation have improved to the point where two persons can complete a field campaign of 150 benchmarks (BMs) in about 20 days using both techniques. The accuracy of the gravity values should be around ± 5 μGals and the BM elevation uncertainties should be around ± 1 cm (Allis et al., 2000; Gettings et al., 1999; 2000). The accuracy of horizontal movements will be better than the vertical accuracy. These accuracies, and the ease (i.e. relatively low cost) with which the measurements can be made, potentially offer new insights into the thermal and saturation (mass) changes occurring in the reservoir.

In this paper we report the preliminary results from the first two trips to The Geysers. These trips were primarily aimed at reoccupying the BMs originally established during the 1970s for precision leveling and gravimetry monitoring (Isherwood, 1977, 1981; Lofgren, 1981; Denlinger et al., 1981; MicroGeophysics, 1979). A secondary aim was to expand the BM network to allow monitoring during 2000-2001 to assess the amplitude of seasonal effects due to annual rainfall variations. Longer term, it is anticipated that field campaigns will be carried out annually around the end of the dry season (late fall) using a network of about 150 BMs. This would cover The Geysers reservoir (~ 50 km^2) and a surrounding zone, with an average BM density of 1 per km^2, giving adequate spatial resolution over the 1 – 3 km-deep reservoir.

One of the immediate opportunities arising from the year 2000 reoccupations of the old BMs is to discover the gravity changes that have occurred since the late 1970s. During the three precision gravity surveys of Isherwood in 1974, 1975 and 1977, gravity decreases (uncorrected for elevation changes) ranged to more than 150 μGals. Even although the fraction of injected water has gradually increased since then, gravity changes many times this magnitude should have occurred between the late 1970s and 2000. Because parts of the reservoir have subsequently dried out (Barker et al., 1995), and other parts have been newly developed since the late 1970s, significant lateral changes are also expected. In this paper we qualitatively relate the mass changes implied by the observed gravity changes to the production history and make inferences about the average saturation changes.

YEAR 2000 MEASUREMENTS

Two precision gravity campaigns at The Geysers were carried out during July 11-14 and September 11-17. A total of 32 BMs with precision gravity values dating from the late 1970s were relocated and reoccupied during these two campaigns (Figure 1). Included in this set of BMs were five from a network of 50 BMs installed by MicroGeophysics Inc. during 1979 for the purposes of precision gravity monitoring around Unit 15 power plant. Poor production from this part of the reservoir resulted in that plant closing soon after construction. Additional BMs were reoccupied or established during the two campaigns in 2000, and precision GPS measurements were also carried out during September campaign. None of these additional measurements will be discussed in this paper.

A Scintrex CG-3M gravimeter was used for all the new measurements, and the measurement procedure was similar to that described elsewhere (Gettings et al., 1999, 2000; Allis et al., 2000). Most marks were repeated at least once during the same day, and if possible one mark was repeated twice to give further control to the gravimeter drift trend. Each day's measurements were tied to a local base (A238A-W. Healdsburg in June; 7TAM in September) at the start and end of the day. The two campaigns in 2000 were tied with regional BM measurements at Kelseyville (H41), Cloverdale, Jimtown and W. Healdsburg. These regional measurements suggested a 20 μGal decrease at Kelseyville relative to the other three BMs between the June and the September campaigns. This same difference (20 μGal) is implied when the June and September values for the local Geysers BMs are compared using Kelseyville as an origin with constant gravity. The differences are resolved if Kelseyville experienced a fall in the groundwater level between the two campaigns (amplitude expected to be several meters). The California Dept. of Water Resources monitors groundwater wells near the Kelseyville, W. Healdsburg, Jimtown and Cloverdale BMs every 6 months. When this year's fall measurement becomes available we will be able to estimate the amplitude of the seasonal groundwater change.

Data reduction techniques similar to those described by Allis et al. (2000) have yielded preliminary gravity values with an estimated uncertainty better than ±10 μGal. This estimate is based on a comparison of gravity values derived for stations occupied during both the June and September 2000 campaigns. Of the 30 BMs with repeat measurements, 29 of the 30 have differences with a standard deviation of 9 μGal. One BM (F1245) has a difference of 80 μGal between the two campaigns; clearly one of the measurements is in error. A more thorough data analysis will be carried out later, and is expected to reduce the average uncertainty to about 5 μGal.

The values have been referenced to the June 2000 measurement at the Kelseyville BM. This BM was assumed by Isherwood to be the stable origin for three precision gravity campaigns between 1974 and 1977. We have assumed here that the gravity value at this BM in 2000 is the same as that during the mid 1970s. Two factors could affect the validity of that assumption: long-term groundwater level changes and/or elevation changes. Groundwater records from the Kelseyville area indicate that the groundwater levels at the start of 2000 were about 2 m higher than those between 1974 and 1977 (depth in 3/00 is 45 feet compared to 50±5 feet during mid 1970s; Figure 3). The gravity effect of this change is likely to be 10–20 μGal, depending on the porosity at the water level (Allis and Hunt, 1986; Pool and Eychaner, 1995). Given the uncertainties inherent in the 1970s and the 2000 gravity campaigns, and the amplitude of the differences at The Geysers during that time (100–700 μGal), we have not made a correction for this factor. We have also assumed the elevation of the BM has remained unchanged. This should be able to be confirmed once our GPS measurements are processed. Mossop et al. (1997) assumed that the elevation of BM V626 remained unchanged between 1977 and 1996. Both BMs are about 15 km from The Geysers reservoir, and our recent GPS survey included the two BMs.

RESULTS

Gravity Changes Between 1977 and 2000

A plot of the gravity changes between the late 1970s (1977- 1979) and 7/2000 assuming the gravity at Kelseyville is unchanged is shown on Figure 4a for the 32 BMs with repeated measurements. The gravity changes in Figure 4a are uncorrected for the elevation changes that are known to have occurred at The Geysers. Despite this, strong gravity decreases are evident towards the southeast part of the BM network (Units 13, 18, 20, Figure 1b) but around the older production areas in the northwest part of the network (Units 1 – 6), the changes vary between +100 µGal and –100 µGal. There is a major discrepancy between two nearby values (-60 µGal at H1244 and -560 µGal at K1244; they are 100 m apart) that is unlikely to be due to lateral reservoir changes. Although we have not yet checked for BM disturbance (i.e. elevation changes), we suspect that a major road cut 5 m from K1244 sometime after 1977 may explain much of the apparent mass loss at this BM. The gravity change at K1244 is shown on Figures 4a and 4b, but is considered suspect.

The observed gravity changes in Figure 4a require correction for elevation changes if interpretations of subsurface mass changes are to be made. For this, the GPS leveling of Mossop et al. (1997) has been used. Their interpreted elevation changes (subsidence) for the period 1977 – 1996 are shown in Figure 5. If the subsidence has continued at the same rate since 1996, the elevation changes between 1977 and 2000 are approximately 20% greater than those shown in Figure 5. This assumption is reasonable because the maximum subsidence rate of about 4 cm/yr found by Mossop et al. (1997) is similar to the maximum rate observed between 1973 and 1977 by Lofgren (1981).

The correction for elevation changes requires the observed gravity changes to be decreased by 3.1 µGal/cm of subsidence. For the largest subsidence value of 110 cm (90 * 1.2), this increases the magnitude of the gravity decrease by an additional 330 µGal. The resulting, corrected gravity changes for the period 1977 – 2000 are shown in Figure 4b. Those marks with gravity observations but no subsidence values (approximately a third) had their subsidence interpolated from adjacent marks on Figure 5.

The corrected gravity changes between 1977 and 2000 are all negative, ranging between –100 and –700 µGal. As mentioned earlier, the value at K1244 (-750 µGal) is suspect. Although the uncertainty in the 2000 measurements is thought to be ±10 µGal, uncertainties in the changes between the late 1970s and 2000 gravity values are estimated to be at least ±30 µGal.

Gravity Changes between 1974 and 1977

Isherwood (1977, 1981), Denlinger et al. (1981), and Lofgren (1981) studied the gravity and deformation changes at The Geysers during the mid 1970s. These publications did not correct the observed gravity changes for the subsidence that was occurring. Figure 6 shows the gravity changes corrected for subsidence. The corrections use a combination of actual and interpolated subsidence at the BMs. The observed subsidence at The Geysers between the 1974 and 1977 gravity campaigns ranges between 4 and 12 cm. Uncertainties in our interpolated subsidence estimates are at most ±5 cm, which is equivalent to a gravity change uncertainty of ±15 µGal. The gravity effect of the subsidence uncertainty is therefore relatively small. Gravity changes between 1974 and 1977, corrected for subsidence, range between –190 µGal and +50 µGal (Figure 6). The main area of gravity decrease coincides with the operating power plants at that time, and it also coincides with the area of pressure drawdown at that time (Lipman et al., 1977). Around the southwest end of the gravity observations, the changes are close to zero. Testing of wells was occurring in this area by the late 1970s, but it was not until the early 1980s that this area had several power plants operating.

DISCUSSION AND PRELIMINARY CONCLUSIONS

A full interpretation requires a more complete analysis of the measurements and data reduction procedures, as well as analysis of the gravity effects of the varying production and injection histories across the field. In this paper we make a few preliminary conclusions based on the amplitude of the changes, using one-dimensional order-of-magnitude calculations.

A qualitative comparison of the gravity changes between 1974 and 1977 (Figure 6) and between 1977 and 2000 (Figure 4b), suggests the area of maximum net mass loss has shifted towards the southeast with time. In the vicinity of Units 20, 18 and 13, there was negligible production before 1977, so the gravity change (-600 ± 50 μGal) since then represents the total mass loss. In the older part of the reservoir (Units 1 – 8), the greatest changes were around –170 ± 30 μGal for the period 1974 – 1977, and close to –280 ± 50 μGal subsequently. Adding together the gravity effects from these two periods implies a gravity change since 1974 of about –450 μGal. This is still significantly less than that observed further to the southeast. The simplest explanation for the apparently smaller gravity change over the oldest developed part of the reservoir is that production prior to 1974 had removed some of the fluid mass by the time of the first precision gravity campaign. The mass of production fluid prior to 1974 was 85 Mt, compared to 70 Mt in the 1974 – 1977 interval covered by the early gravity campaigns (data from California Dept. of Oil, Gas and Geothermal). This could easily account for northwest – southeast differences in total gravity change seen in Figures 4b and 6.

The ratio of net mass loss to gravity decrease can be used to infer saturation changes (dry-out) caused by production. Neglecting edge effects, the relationship between mass loss and gravity change can be simplified to:

$$\Delta g\ (\mu\text{Gal}) \approx 40\ \Delta M / A \qquad (1)$$

where Δg is the average gravity change as a result of an average mass change, ΔM (in kg), occurring over an average area, A (in m^2). The relationship can be rearranged in terms of the effective density change and the thickness of this density change:

$$\Delta g\ (\mu\text{Gal}) \approx 40\ \Delta\rho\ H \qquad (2)$$

where the density change, $\Delta\rho$ is in g/cm^3, and the thickness, H, is in meters (this is the conventional Bouguer slab relation).

Using Equation 1 first, with the known total mass loss through wells of 1200 Mt, and a reservoir area of about 60 km^2, then the predicted gravity change is about -800 μGal. The uncertainty in this figure is at least 20%, given the uncertainties in the effective area. The assumed 60 km^2 area (roughly 15 km by 4 km) includes the area of NCPA in the southeast, which has contributed to the cumulative mass flow figures. If the effective area of mass loss is 80 km^2, then the predicted gravity decrease is much closer to the maximum observed gravity decrease of between –600 and –700 μGal. We have not yet checked whether this area is reasonable given the spread of production wells at The Geysers.

Applying Equation 1 to the period 1974 – 1977, most of the 70 Mt mass loss occurred over an area of about 20 km^2, based on the pressure decline plots of Lipman et al. (1977), and the distribution of microseismicity at that time (e.g. Figure 1 of Smith et al., 2000). This implies an average gravity change of –140 μGal, which given the uncertainty in reservoir area, agrees well with the observations.

Using Equation 2 for the gravity changes up to 2000, and assuming an average reservoir thickness of 1000 m, the average density change is –0.016 g/cm^3. Assuming the immobile liquid reservoir water has a density of 0.8 g/cm^3, the average pore volume that was initially liquid saturated was 0.02 (i.e. 2% liquid-filled porosity initially, assuming the reservoir is now mostly superheated). This value is within the range used by Williamson (1991) for matrix porosity (1.2 – 4.6%) in his numerical model of the reservoir. After some iterations with the model, the matrix was inferred by Williamson to be 82% liquid saturated initially. His model also assumed that some areas of the reservoir had fractures with up to 30% immobile liquid (fracture porosity 1 – 2%). The total initial liquid saturation in the reservoir therefore ranged between 1 and about 6% of rock volume. The greatest initial liquid saturations in fractures in this model were the region of Units 20, Calistoga, Sonoma, 9-10, and 12. The first three plants are close to the area of greatest gravity change on Figure 4b.

Our initial interpretation of the gravity changes at The Geysers indicate that a quantitative comparison of the gravity changes and the historical production and injection changes will yield useful information about the extent of fluid mining from the reservoir. Since a large part of the reservoir is now superheated (Barker et al., 1995), the challenge for the future precise gravity monitoring will be to see whether new zones of increasing liquid saturation due to the enhanced injection rates can be delineated (Allis et al., 2000).

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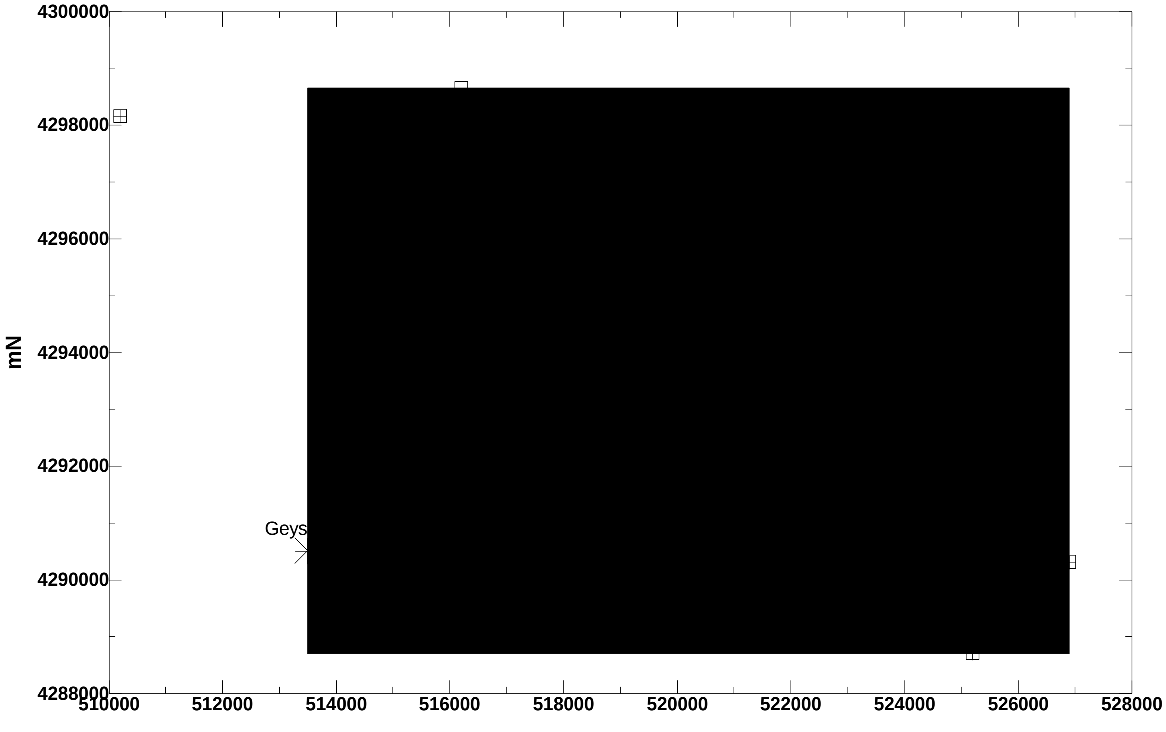

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Fig. 1a. Locations of benchmarks reoccupied during the 2000 surveys and used to determine the gravity changes between the late 1970s and 2000. Squares with crosses are active power plants; open squares are retired plants.

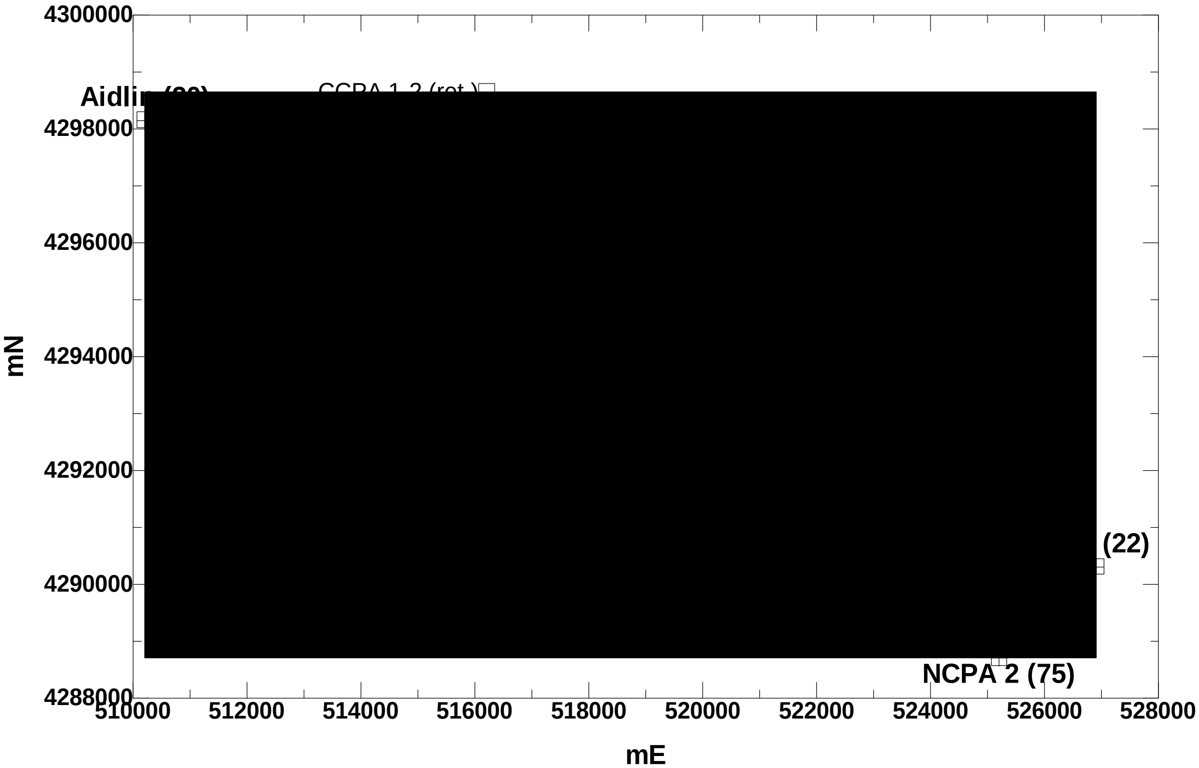

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Fig.1b. Map of Geysers Power Plants. Boxes with plus signs are plants operating in 1999. Open squares are plants that are now retired. Number in brackets is MW output in 1999.

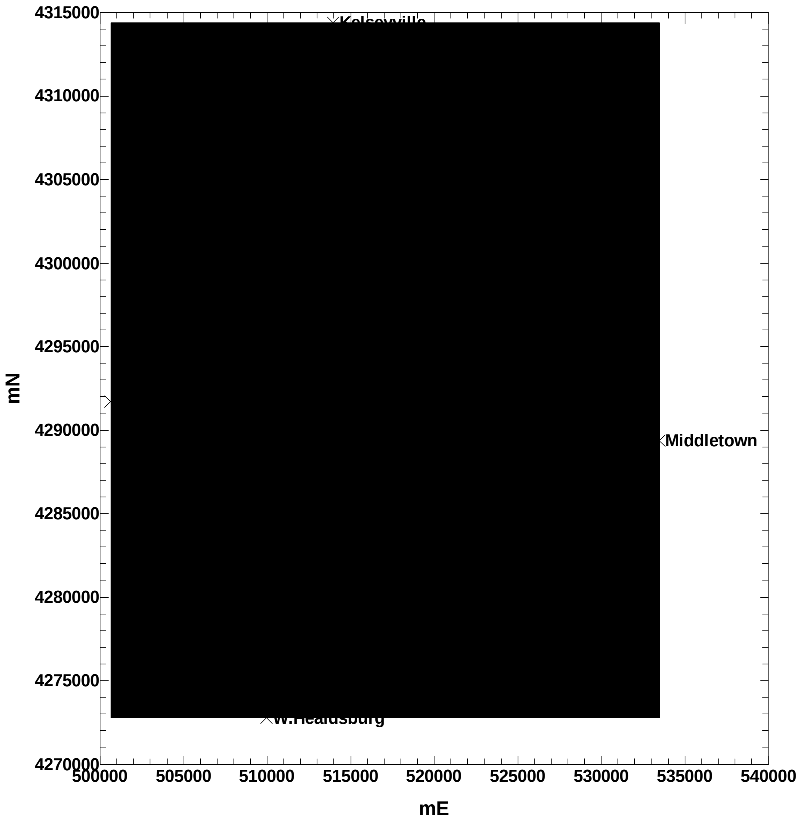

Figure 2. Regional benchmarks established during the two campaigns in 2000. Kelseyville is the origin for the gravity changes between the 1970s and 2000. V626 was assumed by Mossop et al. (1997) to be a stable mark when comparing 1970s leveling and 1996 GPS data. Unlabeled crosses are the 1970s BMs that were reoccupied during 2000 (labeled in Figure 1). Dots outline the approximate reservoir area.

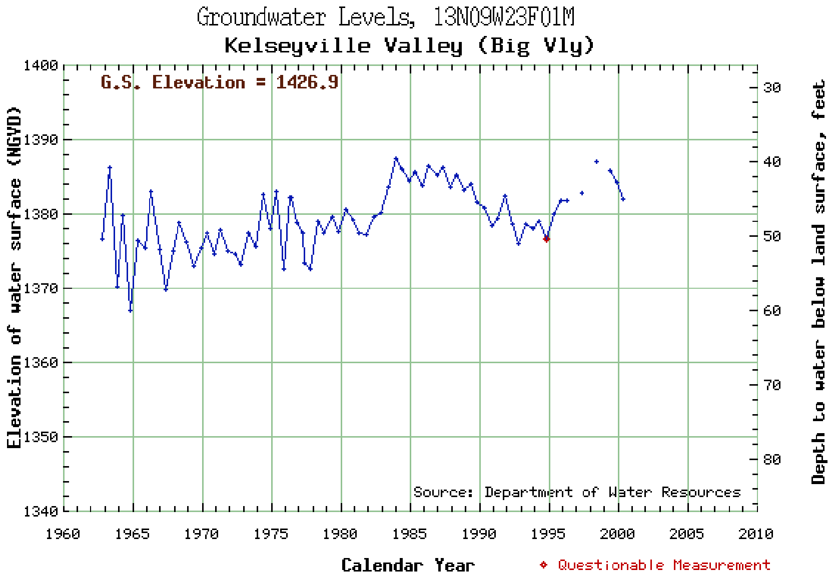

Figure 3. Trend in groundwater level from a monitor well near Kelseyville. Plot taken from web site of California Dept. of Water resources.

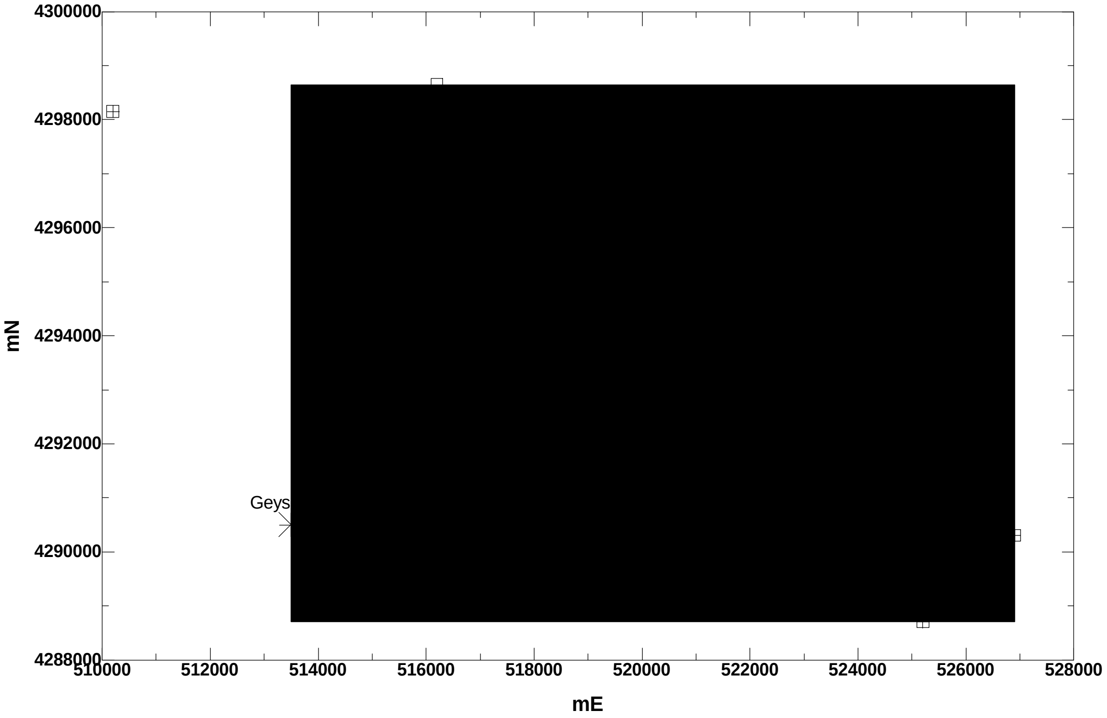

Figure 4a. Observed gravity changes at The Geysers between 1977 and 2000 (μGal). These changes have not been corrected for elevation changes, and assume the gravity at Kelseyville has been constant. Squares containing plus symbols are active power plants, and open squares are retired power plants (from Figure 1b).

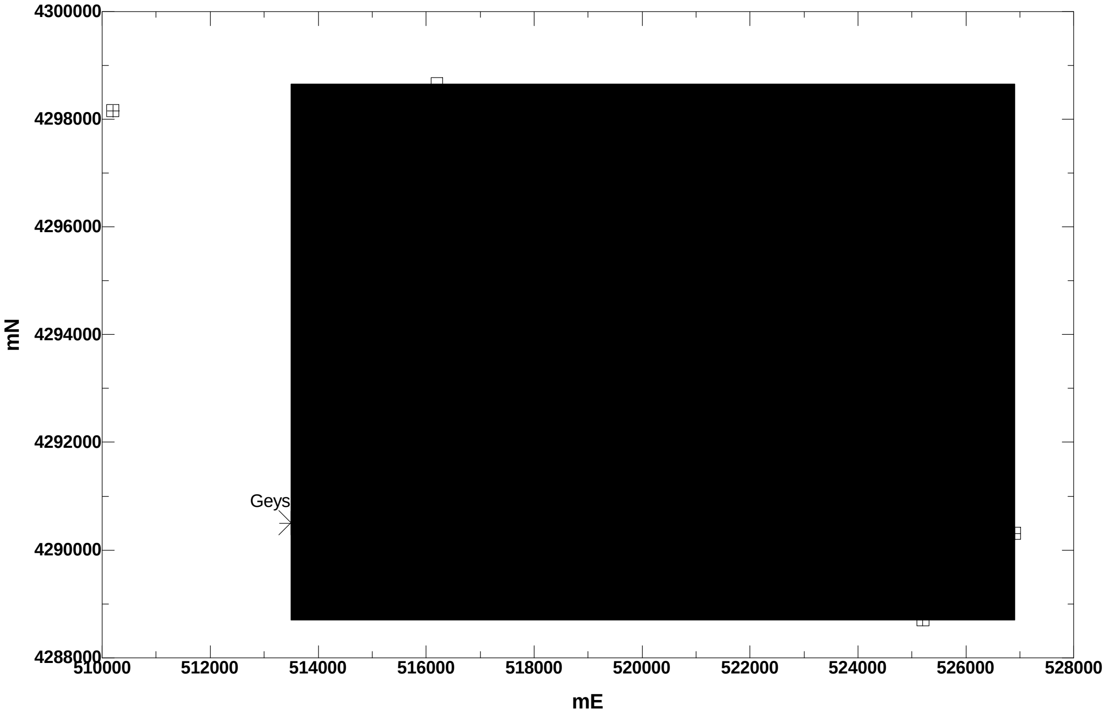

Figure 4b. Gravity changes (μGal) between 1977 and 2000, corrected for elevation changes. The -750 μGal point NW of Cobb Mtn is suspect.

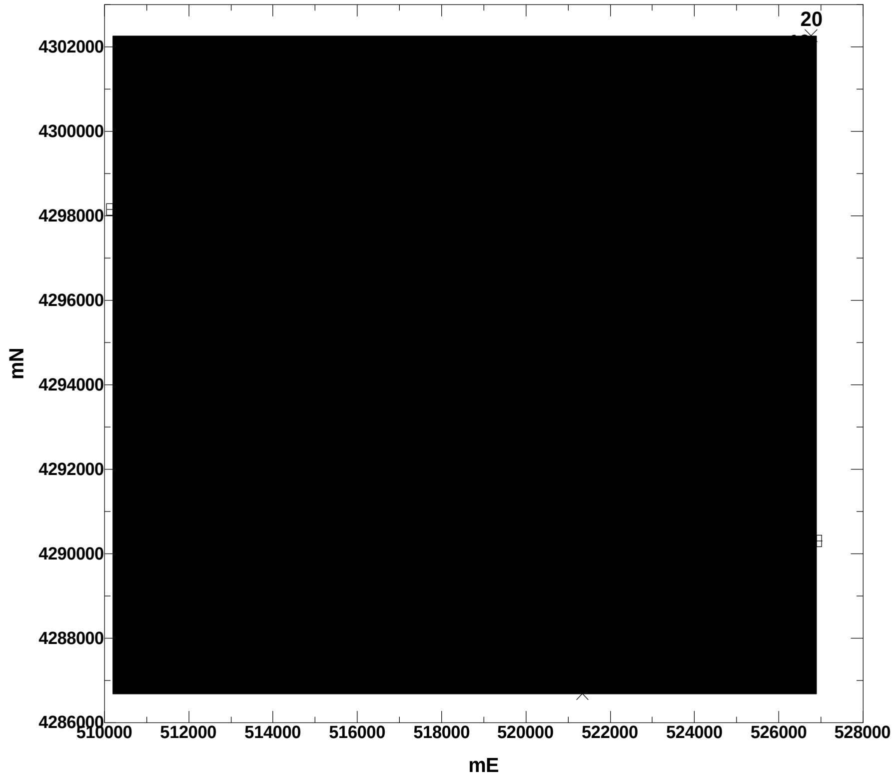

Figure 5. Ground subsidence, 1977 - 1996 (cm; Mossop et al., 1997). Interpretation assumes monument V626 (Figure 2) 5 km NE of the upper right corner of the map remains at constant elevation. Symbols the same as in Figure 1.

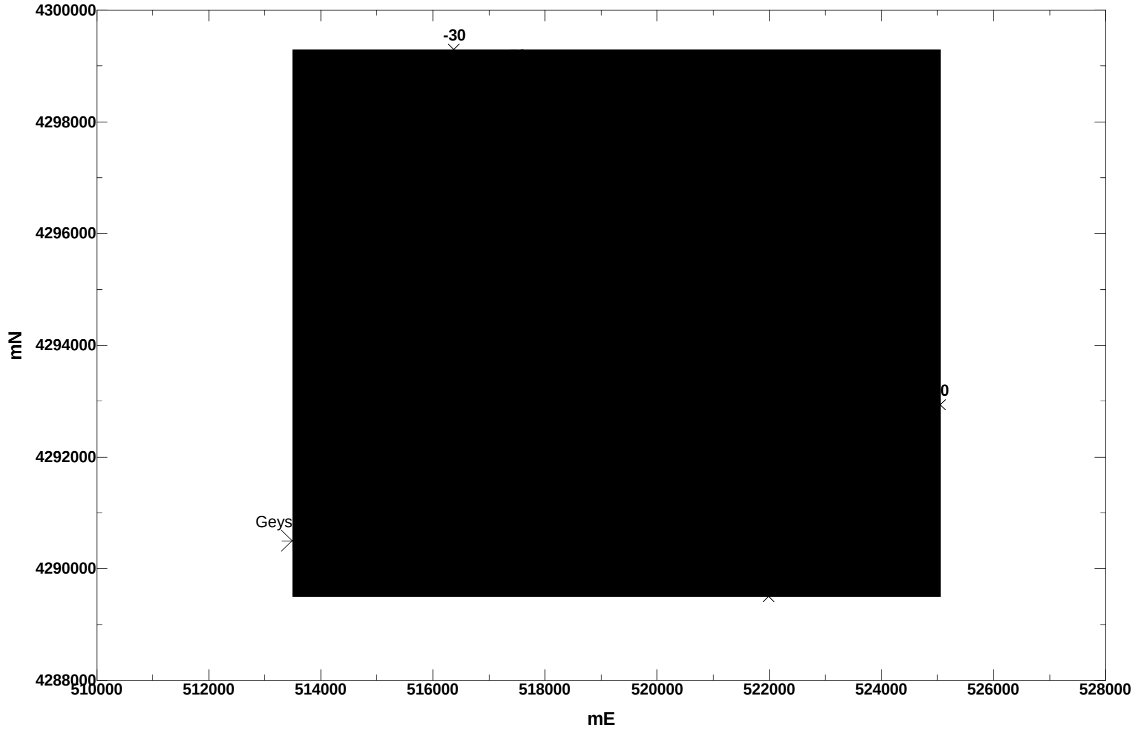

Figure 6. Gravity changes (μGal; 1974-77), corrected for elevation changes. (modified from Isherwood, 1981; refer to text).