PROCEEDINGS, Twenty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 2000
SGP-TR-165

PRECISE GRAVIMETRY AND GEOTHERMAL RESERVOIR MANAGEMENT

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ABSTRACT

Modern portable gravimeters can routinely achieve a 5 ugal uncertainty with careful measurement procedures involving multiple station occupations in the same day, and stacking of readings over at least 15 minutes during each occupation. Although further improvements in gravimeter accuracy are feasible, other practical factors relating to repeat surveys of geothermal fields make such improvements of limited value. The two most important factors are benchmark elevation variations (3 ugal/cm) and groundwater level fluctuations (5-10 ugal/m). Dual frequency GPS receivers can give elevations to about 2 cm after 30 minutes of recording, and for reducing groundwater uncertainties, repeating the surveys during the same season coupled with checks of groundwater monitor wells is advisable.

Simple models are presented for the gravity effects of evolving steam zones at Wairakei field, Dixie Valley field, and The Geysers field. Changes during the main pressure-drawdown phase of development probably caused gravity decreases of 200 – 1000 ugal, but subsequent changes would have been much smaller in amplitude. Gravity monitoring is able to discriminate between steam zone dry-out and steam zone resaturation. However the amplitude of gravity increases associated with individual injection wells is often small and may not be resolvable with annual surveys. Once fields have passed their initial pressure-drawdown phase and the rate of gravity change decreases, the frequency of gravity surveys should be decreased.

INTRODUCTION

Precise gravimetry has been used to monitor the effects of geothermal development at many fields, particularly outside the U.S., but examples where gravity changes have been integrated with reservoir changes are few. In their review of the potential amplitude of gravity changes due to development, Allis and Hunt (1986) showed that the dominant cause of gravity change in liquid-dominated reservoirs is a change in the liquid-vapor distribution at depth. This may occur when steam and/or gas displaces water from pores during the early pressure-drawdown phase of development (causing a gravity decrease), or when injection water floods a previously unsaturated zone (gravity increase). If the pressure changes are known, the gravity changes can be used to constrain the extent of the saturation changes. Assuming 1-D geometry, the gravity effect Δg, of a change in saturation Δs, over an aquifer thickness Δh, is given by:

$$\Delta g = 2\pi G\phi(\rho_w - \rho_v)\,\Delta s\,\Delta h \qquad (1)$$

where ϕ is the porosity in the zone of saturation change, ρ_w is the density of the pore water, ρ_v is the density of the pore vapor, and G is the gravitational constant (6.67×10^{-11} Nm^2/kg^2; Allis and Hunt, 1986). For a porosity of 0.2 and a saturation change of 0.5, the gravity change is approximately 3 ugal/m of reservoir thickness experiencing these changes (water density of 800 kg/m^3). Groundwater hydrologists have used Equation 1 to estimate the specific yield of an unconfined aquifer during water level decline (Pool and Eychaner, 1995; Pool and Schmidt, 1997; Pool, 1999). In geothermal situations it is more complicated because steam pressure may vary as well as liquid zone pressures (Fig. 1). If a steam zone expands downwards due to declining liquid reservoir pressure, gravity decreases (stages 1 to 3, Fig. 1). If the steam pressure decline dominates over the liquid pressure decline, then gravity should increase (stages 3 to 4, Fig. 1). In this situation, steam zone thickness changes are related to liquid and steam pressure changes by:

$$\Delta p_w - \Delta p_v = (\rho_w - \rho_v)g\,\Delta h \qquad (2)$$

where g is gravity (9.8 m/s^2). $\Delta p_{w,v}$ are in the form of initial pressure minus final pressure. The resultant relationship between gravity change and liquid change is therefore (Δp in bar):

$$\Delta g(ugal) \approx 400\,\phi\Delta s\,(\Delta p_w - \Delta p_v) \qquad (3)$$

This equation only considers the draining or flooding of a steam zone(s) due to the pressure changes. It ignores other gravity effects such as steam zone dry-out caused by dry steam production, but this could also be calculated (Allis and Hunt, 1986). By graphing the observed gravity change against the changes in deep liquid and steam reservoir pressure (i.e. bracketed pressure terms in equ. 3), the slope of the resulting trend line will be proportional to the apparent specific yield ($\phi\Delta s$). Significant changes in the gravity-pressure trend (i.e. slope) with time most likely indicate saturation changes due to dry-out or water infiltration from above, or non-uniform porosity with depth in the steam zone. Examples are discussed in this paper.

In vapor-dominated reservoirs, the dominant cause of gravity change is dry-out of the reservoir as immobile water boils due to the production-induced steam pressure decline. This is easily calculated from the properties of the fluid and rocks in the reservoir. If the porosity of the reservoir is low (< 0.1, e.g. as at The Geysers), Allis (1982) showed that while two phase conditions still exist in the reservoir,

$$\Delta g(ugal) \approx 110\, H\, \Delta p(bar) \qquad (4)$$

where H (km) is the effective thickness of the steam zone. Between 1974 and 1977, the gravity change over the main producing area at The Geysers ranged between -150 and -200 ugal (Isherwood, 1977; corrected for elevation changes). The pressure decline in this area between 1974 and 1977 was about 1.7 bar (24 psi; Lipman et al., 1977), implying an effective reservoir thickness of 0.8 – 1.1 km (i.e. effective thickness of 2-phase heat exchange). Although the absolute value of the thickness may not be very meaningful, changes in this apparent thickness with time and spatially within The Geysers reservoir could have assisted management of fluid and heat mining from reservoir, particularly near the boundaries. The scale of past, present and future gravity changes at The Geysers is also discussed below.

The purpose of this paper is to review the scale of gravity changes associated with geothermal development by using examples from the U.S. and New Zealand. This review hopefully demonstrates that gravity monitoring can augment other reservoir monitoring data, but that the frequency of surveys has to be commensurate with the amplitude of likely changes, and the accuracy of gravity surveys. Most of the value occurs with long-term monitoring; short-term monitoring (i.e. 1 year or less) is likely to reveal small, ambiguous gravity changes. Hunt (1995) has emphasized the importance of precision gravity surveys beginning early in a field's development, and for gravity stations to be located outside the field and well as inside. However, large gravity changes cannot be expected with all geothermal developments. If the hydrothermal conditions are such that there is limited development of two phase conditions due to production of fluid, then the gravity changes will also be limited (e.g. Dixie Valley field, Nevada). If the saturation changes are occurring deep in the reservoir, then the gravity method may have poor resolution. The strength of gravity fields decays inversely with the square of the distance from the center of mass, so when 2- to 3-D effects are considered, density anomalies that are significantly deeper than their lateral dimensions are difficult to resolve. Current injection at The Geysers provides insight on what is resolvable, and is discussed below.

In this paper, gravity calculations are based on either 1-D assumptions, or 2.5-D forward modeling (using GM-SYS, NWA, 1994). All gravity changes are assumed to be corrected for elevation changes, and therefore only reflect mass changes at depth. The value of coupling a gravity change module to 3-D reservoir simulators has been demonstrated over the last decade (e.g. Atkinson and Pedersen, 1988; San Andres and Pedersen, 1993; Hunt et al., 1990; Kissling and Hunt, 1992; Hunt and Kissling, 1993; Ishido et al., 1995; Nakanishi et al., 1998; Sugihara and Ishido, 1998; Osato et al., 1998). These simulators usually carry out forward calculations of the gravity changes based on the computed saturation changes. Advances in this area will be possible once inverse gravity modeling methods (Graterol, 1998) are applied to geothermal reservoirs. One potential weakness of numerical simulations is that the block size and structure may not be ideally suited to the more shallow parts of the reservoir where changes in pore fluid saturation may be dominating the gravity change signal. It is therefore advisable that some direct modeling of the gravity changes be carried out *in addition to* simulator modeling. Such gravity models should be closely linked to the changes in fluid characteristics based on both well logs and production wellhead monitoring.

Research on the application of numerical simulators to gravity changes is continuing, but it is not considered further here. The pressure unit of bar is used throughout this paper. 1 bar = 0.1 MPa or 14.5 psi.

MEASUREMENT ACCURACY

Two important factors affecting the value of precision gravimetry for geothermal reservoir monitoring are measurement accuracy, and extraneous causes of gravity change such as elevation changes and shallow groundwater changes. For benchmark elevation control, modern GPS techniques are likely to replace the traditional surveying techniques (Mao et al, 1999). The new techniques can be carried out more cheaply and rapidly, and at the same time as the gravity survey, but they do not have the accuracy of traditional line-of-sight surveying. After 30 – 60 minutes of recording with dual frequency GPS instruments in differential mode (referenced to a stable base station, ideally < 10 km away), the elevation uncertainties should be less than 2 cm. This implies a corresponding gravity uncertainty of 6 ugal. If sub-centimeter-scale uncertainties are required, measurement times at each benchmark need to be several days. This is impractical for a field-wide gravity survey which may involve measurements at 50 – 100 benchmarks. We are currently experimenting with the use of GPS techniques for benchmark elevation monitoring in association with precision gravity monitoring, but at the moment it is premature to draw conclusions.

Variations in groundwater level and soil saturation are harder to quantify. Experience in New Zealand and Dixie Valley field, Nevada, has shown seasonal variations in groundwater level of around 1 m. Although this could be associated with a gravity change of 10 ugal for high porosity soils, the effect can be minimized by correcting for observed groundwater level changes at several sites, and by referencing all gravity measurements to base stations with assumed constant gravity. In regions of high rainfall and high relief, the rainfall effects are larger, and more difficult to predict. Nakanashi et al., (1998) showed water level variations up to 10 m are possible after periods of heavy rainfall (2.4 m/y average rainfall at Oguni field, Japan). Although they suggest elaborate monitoring techniques for reducing the uncertainties in groundwater effects to ± 10 ugal, a more practical procedure is to carry out the measurements in the same season. The gravity effects of groundwater changes should be minimal (< 5 ugal) if repeat groundwater level measurements in monitor wells at the time of the gravity survey show few changes. In arid climates such as the U.S. Basin and Range, groundwater changes are much smaller, and more frequent surveys may be feasible.

The other major source of uncertainty is inherent instrument inaccuracy. Most early precision-gravity surveys of geothermal fields typically had uncertainties of several tens of ugals. Although precision field gravimeters have had a theoretical sensitivity of 1 ugal for at least two decades, changes in the meter response with time due to the effects of drift and tares has meant that 10 ugal repeatability has been a challenge. However the new range of precision gravimeters with automatic electronic readings and a variety of data recording options have the potential to decrease measurement uncertainties significantly. The optimum use of these instruments for geothermal reservoir monitoring has not been published, and it appears there is no consensus amongst the users. We have therefore been experimenting over the last 12 months with optimizing measurement and survey techniques using a Scintrex CG-3M gravimeter. Measurements at approximately 1–2 monthly intervals have been carried out at 8 benchmarks in Salt Lake City, and three fieldtrips to Dixie Valley field have been made. The last two surveys at Dixie Valley involved complete gravity and GPS surveys at 60 benchmarks widely spaced around the field. Space limitations in this paper preclude detailed discussion of the findings and results, so only a brief review is given here.

Fig. 2, shows (almost) raw data from two days of gravity measurements at Dixie Valley. Each data point is the average of 30 seconds of recording by the gravimeter, which takes readings every second. The Longman earth tide effect has been subtracted from the data (by the instrument). The occupation of each benchmark was typically 15 – 20 minutes, giving at least 30 gravity values and potentially showing a short-term drift trend due to the handling history of the meter immediately prior to set-up at that benchmark. Each benchmark is revisited at least once during the day, and at least one base station is occupied three times during the day. The gravimeter is also left running continuously overnight at a base station, giving a long-term drift trend (not shown here). In Fig 2, a constant value of gravity has been subtracted from each benchmark to yield a gravimeter drift trend for the day. The subtracted value is the gravity value for that benchmark, relative to that at the base station. In the case of Oct 30, 1999, the drift was negligible. However on Oct 29, a sinusoid is apparent, as well as two tares during the afternoon. A feature of the CG-3M is an apparent “elastic” recovery period after a tare, with the effects decaying exponentially over the following hour or so (depending on the severity of the tare). In nearly all cases, the tare is in the direction of decreased apparent gravity at the benchmark, with a recovery period of slowly increasing gravity.

We are still in the process of developing automated procedures for reducing the data. An initial reduction of the data from the two full surveys at Dixie Valley (5 months apart; 60 benchmarks), yields an average difference between the gravity values at each benchmark from the two surveys of + 2 ugal. The standard deviation of these differences is 8 ugal. Because our measurement technique improved between the two surveys, we believe a measurement uncertainty of 5 ugal is routinely achievable with careful handling of the gravimeter. Such a survey can cover between 8 – 12 new benchmarks in a day, meaning a field-wide survey of 50 – 100 benchmarks can be carried out by one person in 2 – 3 weeks. An additional person would be needed for concurrent GPS measurements.

LARGE TWO-PHASE LIQUID RESERVOIRS – WAIRAKEI FIELD

Fluid production from liquid reservoirs which are at, or near, boiling point in some part of the reservoir usually causes large gravity changes due to the saturation changes. Published examples are Bulalo and Tiwi in the Philippines (San Andres and Pedersen, 1993; San Andres, 1992) and Wairakei and Ohaaki in New Zealand (Hunt, 1995; Hunt, 1997). The long history of gravity monitoring at Wairakei provides an outstanding example of the ability of the technique to reveal information about steam zone evolution which is not obvious from traditional monitoring methods (Fig. 3). A widespread steam zone formed at Wairakei due to the 25 bar liquid reservoir drawdown between the late 1950s and 1970s. The eastern borefield was part of the production borefield until the 1980s with the shallow steam zone there experiencing a relatively rapid pressure decline during the 1960s and 1970s. The steam zone in West Wairakei has undergone a more gradual pressure decline, accelerating in the mid-1980s when replacement production wells began to be drilled here (Fig. 3a). West Wairakei (Te Mihi) has been the site of some very powerful dry steam wells (~ 20 MW) tapping the steam zone at 300 – 500 m depth (Clotworthy et al., 1999). After an early period of decreasing gravity over most of the field, the gravity trends over the eastern and western steam zones have been very different since the 1970s (Fig. 3b). In the east, gravity has increased by around 400 ugal, but gravity has been almost constant in the west (± 50 ugal; Hunt et al., 1998; Carey et al., 1998).

When the gravity changes are plotted against the pressure differential in Equ. 3, the differences in steam zone response between east and west Wairakei are highlighted. In the east, rapid downward expansion of the steam zone is consistent with a saturation change of 0.8 (for average porosity of 0.3). This implies a liquid saturation in the steam zone by 1967-75 of 0.2. However since then, the large increase in gravity with no significant differential pressure change implies invasion of the steam zone by water. The vertical pressure regime here suggests that this has occurred by downward drainage through the overlying mudstone “confining” layer. In contrast, the west Wairakei steam zone also expanded downwards during the 1960s, but with a saturation change of only around 0.2 (assuming 0.3 porosity). The liquid saturation of the steam zone was therefore about 0.8. The lack of gravity change since the 1980s despite a 7 bar decrease in the pressure differential means that local production of steam is causing dry-out of the steam zone. Apparently the gravity decrease due to dry-out approximately matches the gravity increase due to rising reservoir liquid level. Further analysis of these changes is possible, but is beyond the scope of this paper.

SINGLE-PHASE LIQUID RESERVOIR – DIXIE VALLEY FIELD

In contrast to Wairakei field with its laterally extensive steam zone (~10 km^2), liquid reservoirs which are relatively deep and not of very high temperature may remain largely single phase during development. The gravity changes will therefore be small, assuming the reservoir is confined and not in good communication with near-surface groundwater. However, most developed geothermal fields under development today were discovered because the presence of a thermal outflow zone, which encouraged exploration activity. Reservoir pressure drawdown will propagate to shallow depth in the outflow zone, possibly allowing gravity monitoring to provide useful information on the relationship between the shallow hydrology and the deep reservoir.

Dixie Valley field, Nevada provides a good test of the value of gravity monitoring in such an environment. The main production zones are at about 3000 m depth, where the temperature is 230 - 240°C (Benoit, 1999; 1995; Blackwell et al., 1999; Hulen et al., 1999). There has been no boiling within the production zone, and liquid-phase tracers are ideal for tracking the return of injectate (Rose et al., 1998). The field has an outflow zone with some fumaroles and thermal ground. Since the power plant was commissioning in 1988, a 1 km^2 area coinciding with this outflow zone has had changes in thermal activity and some subsidence, both linked to pressure decline as the original, subsurface hot liquid outflow ceased (Allis et al., 1999). Recently, Oxbow Power Co. has been pumping cold groundwater into a shallow well in this area at approximately 60 kg/s (1000 gpm into well 27-32) in an attempt to increase reservoir pressure. We are presently testing the precision gravity method over this field (Gettings et al., 1999).

In this paper we consider the outflow model of Allis et al., (1999), and calculate the gravity effects of the first decade of pressure drawdown. The amplitude of the present phase of increased injection is also considered. We assume here the shallow pressure drawdown is limited to the immediate area of the known outflow zone (Fig. 4). The geometry of the drained zone is highlighted in the figure. The liquid-steam interface is assumed to now be at 500 masl, and the drained pore volume ($\phi\Delta s$) is assumed to be 0.1. Despite the restricted geometry of the drawdown zone, 2.5-D gravity modeling (± 1 km either side of cross-section) suggests a gravity change anomaly of almost -200 ugal could have occurred (Fig. 4). If gravity had been monitored since 1988, the anomaly could now be of assistance in targeting shallow injection into the outflow zone. Major uncertainty presently exists over just where the original upflow existed beneath the fan, and where the injectate is currently flowing down towards the reservoir.

A rough estimate of the magnitude of gravity effects due to the increased injection rate into the upflow zone is possible if it is assumed that all the injectate accumulates in the restricted volume of the upflow zone. This would occur if the reservoir was incompressible, and therefore is gives an upper limit for the gravity change. Using the same 2.5-D geometry as before, and assuming the mass increase occurs at 500 m asl, the 20 m increase in water level after 1 year of increased injection causes a 5 ugal peak anomaly, similar in wavelength to the anomaly shown in Fig. 4. If the injectate is accumulating at shallower depth, or is spread over a smaller area, the anomaly amplitude increases to the order of 10 ugal/year. At least two years of injection appears to be needed to see a significant gravity effect in the outflow zone due to the local water injection .

Drawdown due to the production borefield extends almost 2 km northeast of the northern borefield, where the water table in well 76-28 is now at 550 m depth (Williams, 1997). The shallow, cold groundwater table in and around the Dixie Valley geothermal field lies between 10 and 20 m depth, and has not changed greatly with development (authors' unpublished data). The extent to which deep reservoir drawdown within the field has caused shallow drainage beneath a perched groundwater zone adjacent to the Stillwater Rangefront is unknown. The precision gravity surveys we are presently carrying out in Dixie Valley may shed light on this, and the recharge mechanisms of the field.

VAPOR-DOMINATED RESERVOIR – THE GEYSERS

Apart from the three-year period when Isherwood (1981) carried out gravity monitoring at The Geysers, and brief monitoring at one location by Goodkind (1986), the long-term gravity change is unknown. An estimate of the gravity change is possible based on the annual mass withdrawal rate if it is assumed that natural recharge to the reservoir has been negligible (Fig. 5). If the net mass extracted is assumed to be spread over a 50 km^2 reservoir area, the cumulative anomaly would now be about -1000 ugal. This is equivalent to a 2 km thick reservoir being depleted of 3% liquid volume (i.e. $\phi\Delta s$ = 0.024), which seems reasonable given the extent of super-heat now in the reservoir, and estimates of average porosity (ϕ = 0.02 – 0.06; Gunderson, 1992; Williamson, 1992). The observed gravity declines of up to 50 ugal/year measured by Isherwood (1981) in the mid 1970s compares to 30 ugal/y predicted in Fig. 5. This difference can be explained by the localized production occurring at that time over about half the total 50 km^2 Geysers reservoir area. With the commissioning of the Southeast Geysers Effluent Pipeline (SEGEP) project, the amount of injection water is becoming similar in magnitude to produced mass of steam. If this water is evenly dispersed, and steam is also evenly extracted, the gravity anomalies should be small. However, the Geysers reservoir is far from homogeneous (Barker et al., 1995), so gravity monitoring still has the potential to monitor mass anomalies and assist management of future heat mining at The Geysers.

A key difference between the liquid- and vapor-dominated reservoirs is that drainage of liquid reservoirs tends to be from beneath confining layers and may be laterally extensive, whereas the much higher compressibility of vapor-dominated systems (Grant and Sorey, 1979) results in more local heat and mass mining around production wells. Injection of water into liquid reservoirs increases the liquid head, which even under heavy production rates is often at less than 1 km depth. In vapor-dominated systems, the drainage of water is predominantly downwards, with lateral spreading of water dependent on the presence of sub-horizontal low-permeability baffles (Pruess, 1992). At The Geysers, liquid-phase tracers such as tritium indicate that injected water can travel at least 1 km laterally from injection wells (Voge et al., 1994; Adams et al., 1999). However, microseismicity also shows that the effects of injection water can extend downwards to at least 4 km depth (Stark , 1992; Beall et al., 1999). If the injectate is accumulating at 3 – 4 km depth, the gravity changes measured at the surface will be difficult to resolve on a well-by-well basis, as is shown below (Fig. 6).

The microseismicity clouds associated with injection beneath The Geysers should not be interpreted as the main rock volume where injectate accumulation has occurred. Accepting the interpretation of Stark (1992) that many of the injection-related earthquakes are from local fractures becoming water-filled, resulting in hydraulically-induced fracturing, the main mass (density) change occurs due to injectate accumulation at the top of the liquid-filled zone. However, the pressure change has maximum effect at the bottom of the liquid zone where hydraulic pressures approach the local fracture/stress release threshold. Consideration of the volume of injected water also shows that the micro-seismic clouds are far too large to be new water accumulation volumes (Fig. 6; injectate volumes assume porosity of 0.01). The first portion of injected water may fill the deep fractures if they were not already liquid-filled, but once filled, they will remain stable as single-phase liquid (assuming deep temperatures of <300°C; in the very high temperature reservoir of northern Geysers this may not apply). If the reservoir above the injection point has a temperature of >200°C, with a vapor pressure of around 20 bar, it may take only 200m of a vertical fracture zone to be liquid-filled beneath this point for there to be no boiling in the fracture at greater depth. The hope with deep injection is that lateral movement of water in these fractures will steadily dissipate the hydraulic head beneath injection wells and allow boiling at the margins of the spreading liquid plume.

The gravity effects of increased injection associated with SEGEP have been assessed along a profile crossing several injection wells (Fig. 6). The microseismicity maps from Beall et al., (1999) have been used as a guide to possible injectate accumulations. The mass of injected water remaining in the reservoir after the first year of operation is derived from the known injection mass into each well, reduced by the fraction of injection-derived steam returned to production wells (given in Goyal, 1999; and Adams et al., 1999). For the three injection wells considered here along profile A – B, the injection-derived steam returns were assumed to be 0.6 (42B-33), 0.35 (956A-1) and 0.5 (sum of NCPA wells Q1, Q4, P1,Y5). The residual mass accumulations for each injection site are shown on Fig. 6c. The assumed shape of the mass accumulations was based on the distribution of microearthquakes, with the main density changes assumed to occur near the top of the seismic cloud (as discussed above; fracture volume of 0.01 assumed). The NCPA anomaly is intentionally located at a relatively shallow depth and with a horizontal-tabular shape to investigate its effect on the gravity anomaly. The computed gravity anomalies along the profile (Fig. 6c) show that individually, the maximum gravity effects from the one year of injection range between 1 – 4 ugal, with the amplitude being a function of both the mass concentration, and its depth. The sum of the gravity changes along the profile has a maximum value of 5 – 6 ugal/year which would be barely resolvable based on present measurement precision with surveys one year apart.

As injection water accumulates in sectors of The Geysers reservoir, and the extent of super-heat diminishes, future management of the heat mining process will require improved knowledge of where the residual injectate is accumulating. If injection continues at its present rate, the component of residual injectate in the reservoir will grow, causing a progressively increasing gravity signal. Existing reservoir monitoring tools such as drillhole logging, tracer testing and microseismicity can be augmented with precision gravity monitoring. Gravity monitoring is unlikely to be helpful on a year-to-year basis, but over a 5-year period significant mass accumulations will be resolvable. These may highlight major high permeability trends within the reservoir which were not previously recognized. The gravity changes may also provide insight on the nature of the reservoir boundary zone which is unobtainable from any other data source (i.e. because of a lack of drillholes).

CONCLUSIONS

Large gravity decreases of 100 – 1000 ugal caused by reservoir saturation changes usually accompany the first 10 - 20 years of geothermal field development. Injection into the reservoir limits the amplitude of such changes, but even in fields with largely single-phase liquid, the gravity signature caused by drainage of an outflow zone may provide useful information about shallow hydrological connection with the reservoir. This information could become valuable in later years when maximizing heat extraction from the partially depleted reservoir becomes more critical. At Dixie Valley, such information would now be of assistance with targeting shallow injection of groundwater into the original outflow zone. Repeat gravity surveys every 1 – 2 years during the early stages of pressure drawdown provide information on saturation and porosity in two phase zones which can then be used to calibrate reservoir simulation models. At Wairakei, we have shown that gravity monitoring is very sensitive to differences in steam zone pressure decline due to water invasion or to steam zone dry-out. Repeat gravity surveys during the early stages of field development become increasingly valuable in later development years when replacement drilling for both production and injection is need to sustain the power plant. Differences between the location of the reservoir boundary zone based on gravity change measurements and resistivity or drillhole temperature measurements could yield important information about the permeability regime within the reservoir.

After the initial stage of relatively easy heat extraction associated with production-induced pressure drawdown, many fields enter a phase of heat mining due to water flow through the reservoir, whether it be liquid- or vapor-dominated. As the rate of gravity change diminishes, annual surveys may not resolve significant gravity differences. Good injection wells can typically accept flows of at least 2 Mt/year (~ 1000 gpm), but this mass accumulation is barely resolvable with annual surveys if it dispersing widely (> 1 km^2 area, or at > 1 km depth). However, gravity surveys will still be useful for long-term management of the reservoir because mass balance in the reservoir is an indicator of the heat mining process. The frequency of precision gravity surveys needs to be adjusted based on the scale of change expected in the reservoir, and the uncertainties of the measurements. In some cases a five-yearly frequency may be all that is needed.

ACKNOWLEDGEMENTS

The gravity measurements at Dixie Valley were carried out with logistical assistance from Oxbow Power Co., and with the funding support of the U.S. DOE geothermal contract DE AC0795ID 13274. We

thank Joe Beall and Mitch Stark (Calpine Corp.) for providing electronic copies of the microearthquake data shown in Fig. 6.

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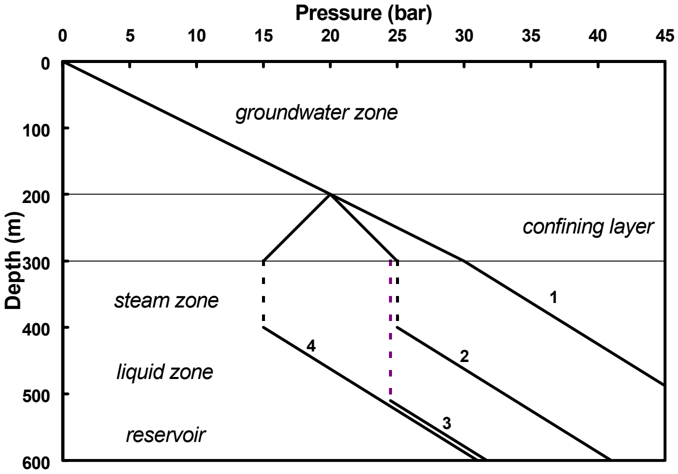


Fig. 1.Conceptual model of steam zone expanding when pressure change is dominated by liquid pressure decline (stages 1-3;gravity decreasing), and shrinking when steam pressure decline dominates (stages 3-4; gravity increasing).

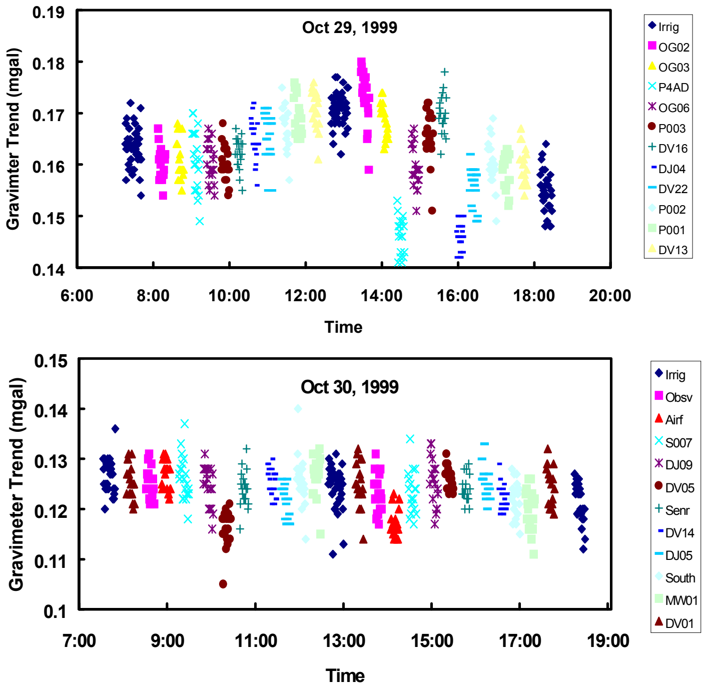


Fig. 2. Example of two days of gravity measurements at Dixie Valley. Each vertical cluster of points comprises 30s instrument integrations recorded over about 15 minutes. Each station was visited at least twice each day. A gravity value for each station has been removed from the data to yield a drift trend for the gravimeter. Note two tares on Oct 29.

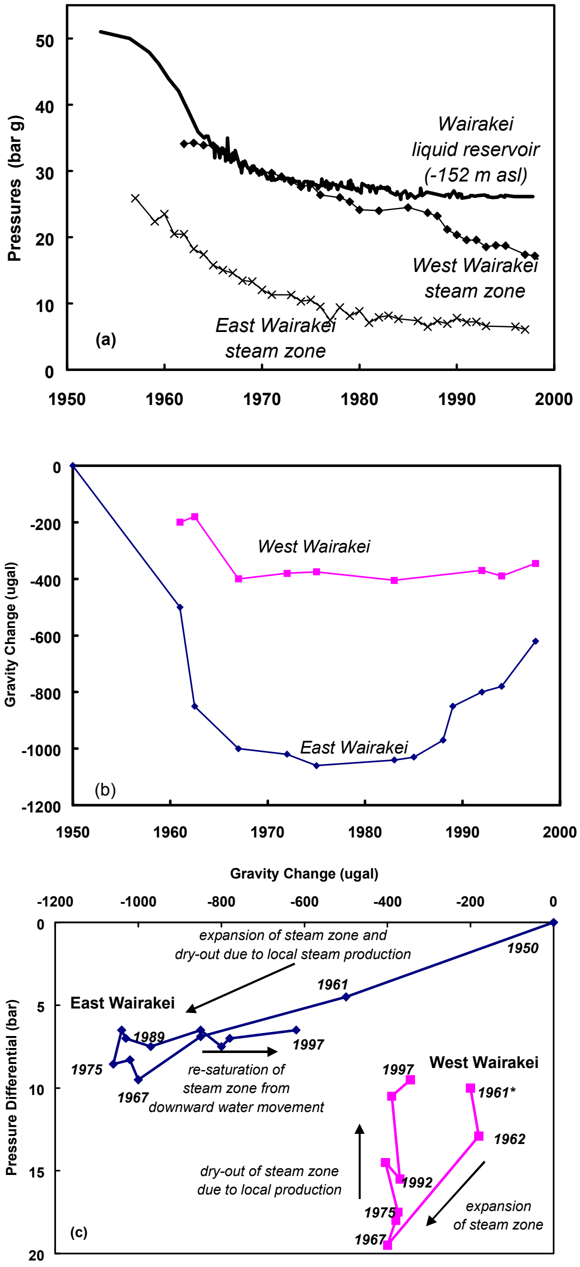


Fig. 3. Trends in reservoir pressure and gravity from the west and east of the field, showing the different responses of the steam zones. The west Wairakei gravity and pressure trends are assumed to begin at –200 ugal and 10 bar in 1961.

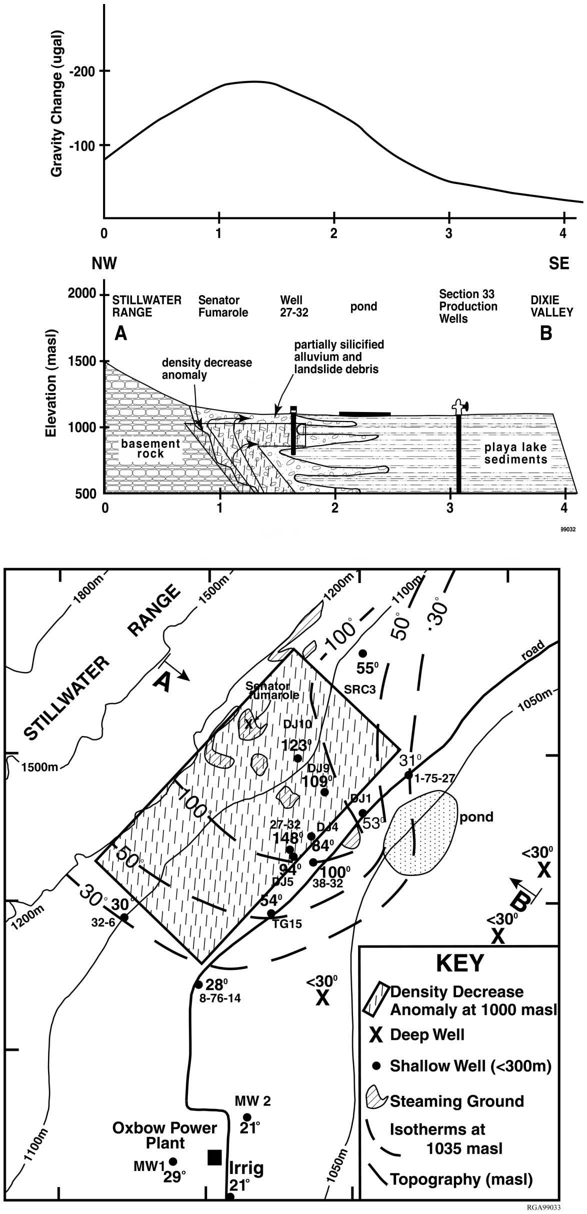


Fig. 4. Calculated gravity anomaly due to drainage of stippled volume shown in cross-section (upper figure) and plan view (lower figure) caused by 10 years of production from production wells at Dixie Valley geothermal field. Stippled volume is assumed to approximate the original liquid outflow zone which is now steam-filled. Calculations assume drained pore volume of 0.1.

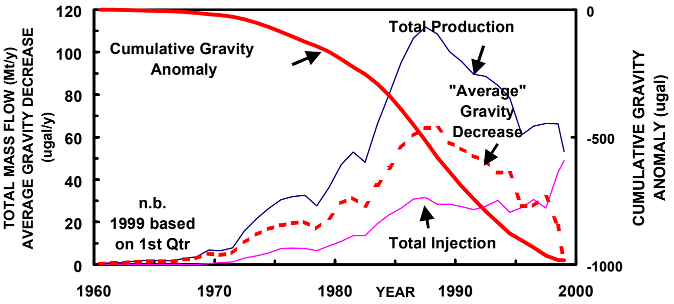
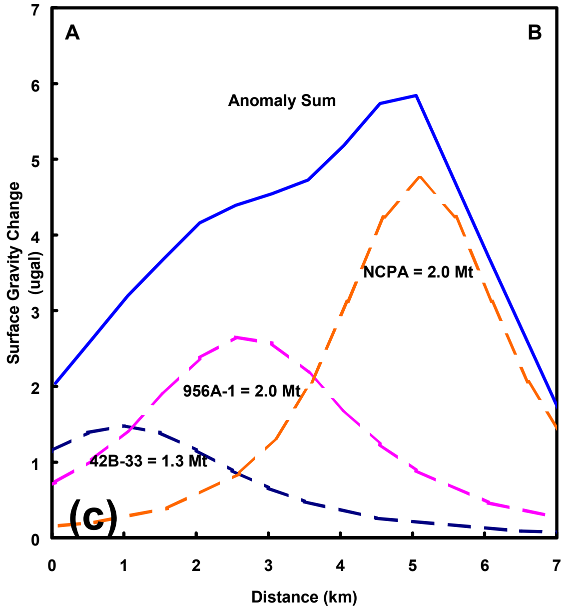
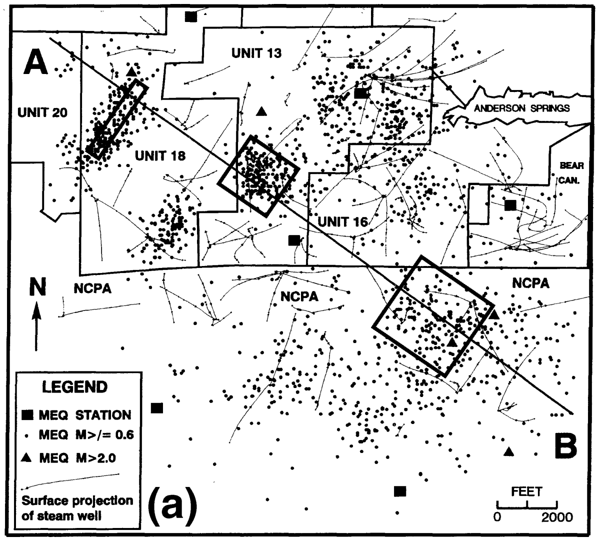


Fig. 5. History of annual steam production and water injection at The Geysers (from CaDOGG), theoretical gravity change caused by the net mass loss. Gravity calculations are based on the mass loss being evenly distributed across the 50 km² area of the reservoir.





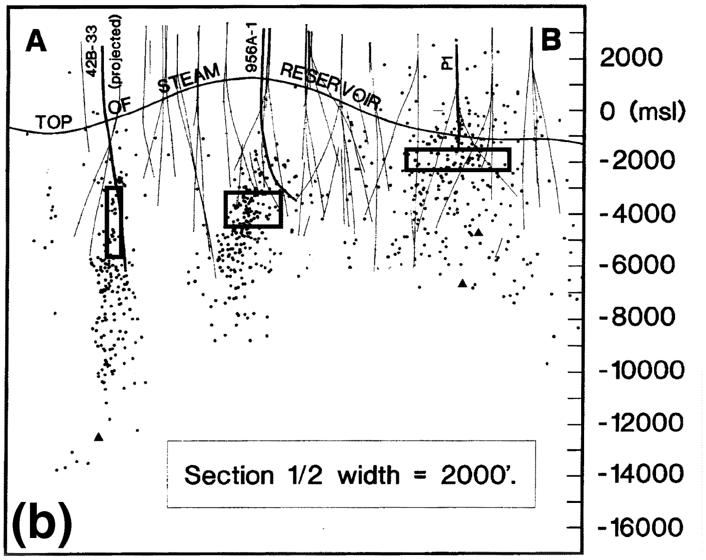


Fig. 6. Computed gravity anomalies based on 1 year of injection in three locations along profile A-B in the Southeast Geysers. The accumulated injectate masses in each case are shown in (c) based on total injection flows and tracer information on precentage of produced injection-derived steam (refer to text). The volume of the accumulated injectate assumes a porosity of 0.01. Microearthquake data is from Beall et al., (1999) and was recorded during the injection period (11/1/97 – 10/31/98). Elevation scale in (b) is in feet.