Potentiality of Continuous Measurements Using a Small-Sized Superconducting Gravimeter for Geothermal Reservoir Monitoring

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Keywords

Superconducting gravimeter, gravity monitoring, geothermal reservoir, continuous recording, super hybrid measurements, CCS

ABSTRACT

Results of continuous gravity measurements carried out at CCS test sites using portable superconducting gravimeters suggest that such gravimeters may be useful for geothermal reservoir monitoring. The most noteworthy advantage is the small initial drift rate, which can be less than 1 microGal/month. It may be possible to detect short term mass redistributions within a geothermal reservoir caused by changes in fluid production or injection rate. One such situation is during the early stages of exploitation when the two-phase zone is expanding rapidly. Another is during field wide shut-ins associated with periodic inspections of the power station. Although such changes have been observed at a few geothermal fields in the past, we anticipate much more success detecting such short term gravity changes using the portable superconducting gravimeter which can detect as small changes as 1 microGal.

Introduction

The superconducting gravimeter (SG) is distinguished from other gravimeters by superior precision, better than 1 nm/s^2 (100 nGal) and by the ability to record gravity continuously over periods of months and longer. Olson and Warburton (1979) first reported the results of continuous measurements at a geothermal field using an SG meter. A one-month data segment obtained at The Geysers field indicates that it is possible to accurately observe the steady decrease in gravity associated with continuous steam production and thus provide the most direct available measure of reservoir recharge. Goodkind (1986) also showed correlations between changes in gravity and condensate reinjection rates at The Geysers. An SG meter is, however, so expensive to purchase and to maintain that it has been impractical for routine monitoring operations. The 3rd generation SG meter has been expected to reduce the maintenance cost. A new hold-

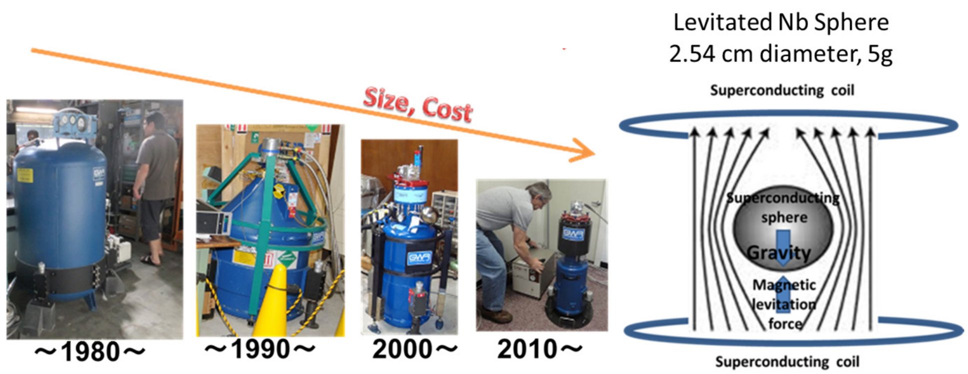

Figure 1. (left): The 4th generation SG meter, model iGrav is a new SG model that has been simplified for portable and field operation, but retains the stability and precision of previous SGs. The higher generation the smaller dewar is used. (right): The sensor is in the liquid helium bath stored inside the dewar.

time dewar was developed using a 4 K refrigeration system. The 4 K cryocooler re-condenses the helium gas as it boils off from the liquid helium bath stored inside the dewar. In this manner, the dewar operates as a closed cycle system with no loss of coolant as long as power is maintained for the refrigerator (Richter and Warburton, 1998). This has reduced man-made disturbances for helium transfers and cryocooler maintenance and allowed operation in remote areas. The 4th generation SG meter model, iGrav, has been simplified for portable and field operation, but retains the stability and precision of previous SG meters (Figure 1).

Numerical models of geothermal reservoirs are never precise, owing to the problem of non-uniqueness. A technology to utilize geophysical monitoring data as well as well data was developed to reduce the inherent non-uniqueness of any mathematical reservoir model (e.g. Pritchett *et al.*, 2000; Ishido *et al.,* 2005; Ishido *et al*., 2015). The technology is based on computer programs, so-called geophysical postprocessors, which calculate changes in observables such as gravity based upon the changing underground condition computed by reservoir simulations (Figure 2). Regarding the geophysical observation technology, Sugihara and Ishido (2008) carried out geothermal reservoir monitoring with "hybrid" gravity measurements, in which absolute gravity measurements provide a reliable reference datum for relative spatial surveys. Then, Sugihara and Ishido (2010) proposed the "super hybrid" gravity monitoring method, which adds continuous recording with an SG meter to the hybrid method. We tried to apply the method in two fields; (1) a geothermal field in Japan, and (2) a CO_2 geo-sequestration test field in the USA (Sugihara and Nawa, 2012). Three years have passed since then. In this paper we review the results and discuss the applicability of the method to geothermal reservoir monitoring. Super-hybrid measurements were tried at both fields, but the expected signals are so small that in this paper we focus on the results of the continuous gravity measurements.

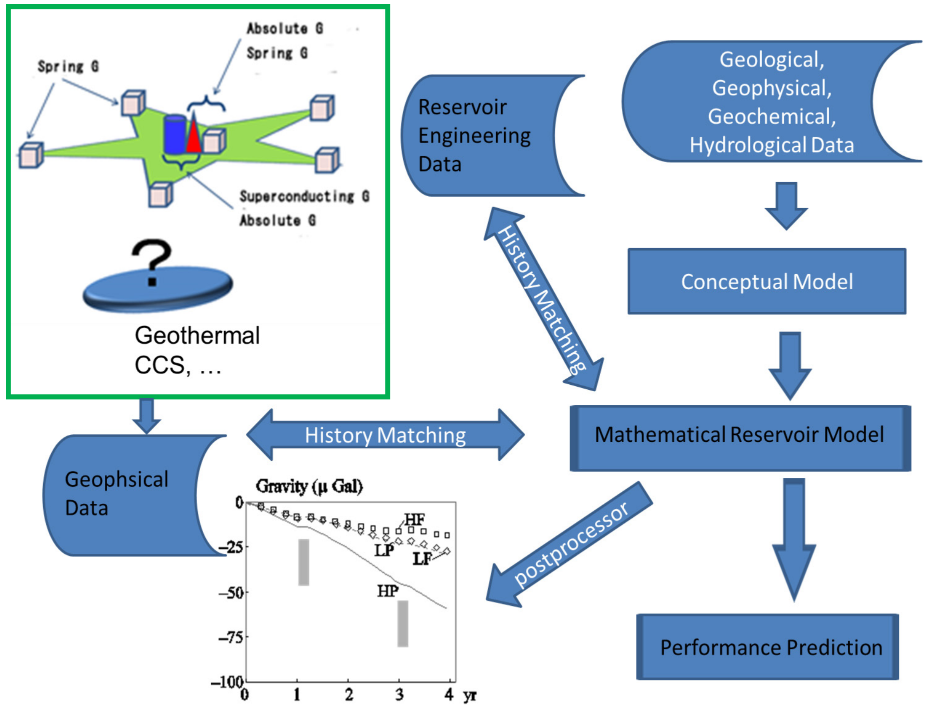

Figure 2. Geothermal reservoir modeling. Postprocessors permit the user to calculate temporal changes that are likely to be observed if geophysical surveys of an operating geothermal field are repeated from time to time. Results may be used to supplement conventional reservoir engineering measurements in history-matching studies undertaken during geothermal reservoir model development (modified from Ishido *et al.,* 2005).

A Trial of Continuous Gravity Measurements for Geothermal Reservoir Monitoring

In Japan, it is quite difficult to exploit geothermal energy without the cooperation of local hot spring operators. In order to approach the problem, a three-year research project started in fiscal year 2010 (2010FY). The purposes of the project were to develop an integrated geothermal reservoir operation system for adequately controlled utilization and to prove that geothermal exploitations can be performed without interfering with nearby hot springs (Yasukawa *et al.,* 2011). The final goal was to develop a reliable monitoring system that can detect small changes in hot spring characteristics caused by nearby geothermal development projects. One of the two fields is Hachijojima Island, a volcanic island in the Pacific OceanPhilippine Sea located 290 km south of Tokyo. A 3.3 MWe geothermal power station has been in continuous operation since March, 1999 in the southern part of the island, and several hot spring wells were also drilled nearby (Matsuyama *et al.,* 2000). Ring structures occur in the area and parasitic volcanoes are present on top of these structures. These fractures channel the up-flow of geothermal fluid. A low-permeability cap rock prevents the penetration of seawater and ground water into the geothermal system. A monitor well was drilled for the project between the power station and one of the hot springs.

We hoped to detect changes in groundwater and hot spring water level with a resolution of 10 cm, which is roughly equivalent to a resolution of 1 microGal by continuous gravity monitoring (Figure 3). At first we intended to introduce an SG meter into the project. The budget, however, restricted us to use rental equipment. We introduced four gPhone meters (a new type of metal spring sensor gravity meter) instead of purchasing an SG meter. In 2010FY we used three gPhone's at the geothermal field for two months. The fourth gPhone was used for parallel measurement with the SG meter at the Matsushiro observatory of the Earthquake Research Institute for two months in order to compare the performance of the two gravimeters. In 2011FY continuous monitoring was carried out using the gPhone gravimeter. Using the data which were obtained, we calculated and compared temporal variations of the drift rate. As a result, drift rates of gravimeters showed various characteristics according to location and elapsed time since installation. In many cases, it took about a month until the initial drift stabilized, that is, the drift rate became quasi-constant. Even after stabilization, the drift rate of the gPhone gravimeters remained a few microGal/day (compared to the nominal drift rate of the iGrav SG meter which is 0.5 microGal/month), although the magnitude of the drift rates were considerably smaller than the several hundred microGal/day of CG-3M portable gravimeters (Nawa *et al.,* 2008). In late December 2011, we detected a gravity decrease of approximately 5 microGal that occurred about 3 days after a groundwater temperature decrease of approximately 1 degree Celsius was observed in the monitoring well. Several other small (microGal level) gravity changes were also observed during the observation period. We attributed the gravity changes to interactions between the aquifer and the hot spring reservoir (Nawa *et al.,* 2012).

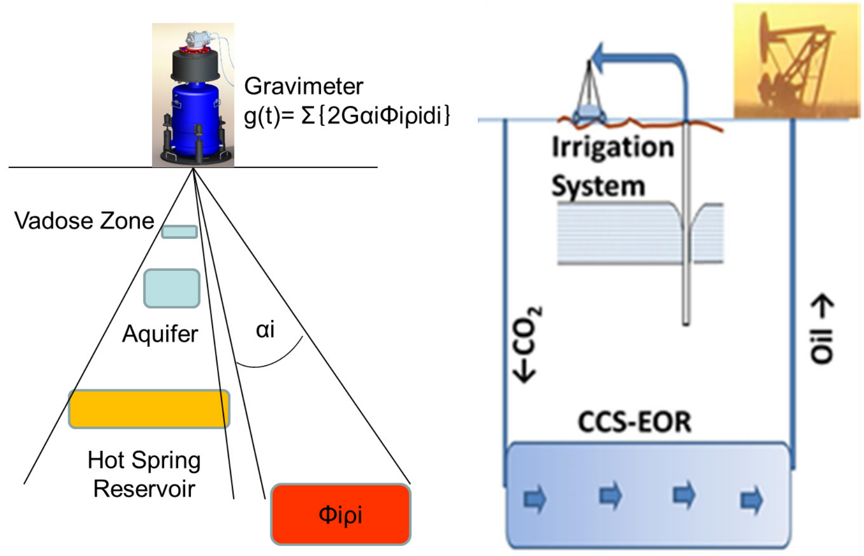

Figure 3. (left): A schematic diagram of sources of gravity changes at the Hachijojima geothermal field. (right): A schematic diagram of sources of gravity changes at the Farnsworth CCS-EOR field

A Trial of Continuous Gravity Measurement for CO_2 Sequestration Monitoring

To appraise the utility the scheme shown in Figure 2 for monitoring CO_2 injected into aquifers, Ishido *et al.* (2011) carried out numerical simulations of aquifer systems. The study used the STAR general-purpose reservoir simulator (Pritchett, 1995) with the SQSCO2 equation-of-state package which treats three fluid phases (liquid- and gaseous-phase CO_2 and an aqueous liquid phase) to calculate the evolution of reservoir conditions, and then used the gravity postprocessor to calculate the resultant temporal changes in the earth-surface distribution of microgravity. These calculations of gravity change suggest that microgravity monitoring can be an effective technique for characterizing the subsurface flow of CO_2 injected into underground aquifers. The calculated signal strengths are not particularly large, but should be detectable using a high-precision continuous gravity measurement technique.

At first we tried to apply super-hybrid gravity monitoring to a CO_2 sequestration test field in Utah as, a part of a the USDOE-funded project with the's Southwest Regional Partnership on Carbon Sequestration project. One of the purposes of our study is the development of lower cost and higher reliability monitoring methods for CO_2 geo-sequestration by complementing standard seismic surveys with various other geophysical techniques, especially gravity monitoring. Two pillars were constructed at the Gordon Creek test site for parallel measurements using an absolute gravimeter and an SG meter (Sugihara and Nawa, 2012), and the first absolute gravity measurements were made using an A10 absolute gravimeter in December 2011 (Sugihara *et al.,* 2013a). Unfortunately the super hybrid measurement was not made at the Gordon Creek site because the testing had to be moved to the Farnsworth CO_2-EOR test site in Texas. The transportable hut was moved to the new site. We again constructed two pillars then conducted baseline measurements and attempted to monitor any response from a large scale CO_2 injection which would be started in 2014.

The results from the SG were evaluated by co-located measurements with an absolute gravimeter (AG) (Figure 4). We decomposed the 225-day continuous gravity data using the program BAYTAP-G (Tamura *et al.,* 1992) into the trend components, tidal components and others (Figure 5). Generally the instrument operated well and performed within specified limits. The trend components are the principal signals of interest for this study. Some spikes in raw gravity signal were observed. These disturbances may be due to local cultural activities such as truck traffic or the operation of heavy equipment near the site. The air conditioning/heating system provided for the observation hut operated well throughout the observation period. All of the instruments are operating normally with no remarkable deficiencies.

Drift of an SG meter can lead to a false interpretation of the long-term gravity change at the SG site. An iGrav SG typically first exhibits a very large drift on the order of 200 microGal which decays rapidly over the first 24 hours. This time interval is discarded due to the large magnitude of the signal. Following this settling period, an iGrav typically exhibits an exponential drift which can be described with two different time constants. These functions are described as the "Initial Drift" or Exp1 and the "Long Term Drift" or Exp2. Within about 4 months of initialization, a properly functioning iGrav exhibits a drift of less than 10 microGal/year, and may approach 0 microGal/year. It is impossible to verify the instrument performance without comparison to data from an AG meter and/or another SG with known characteristics. In the presence of comparatively large and uncharacterized geophysical signals, performance verification without such comparisons is impossible.

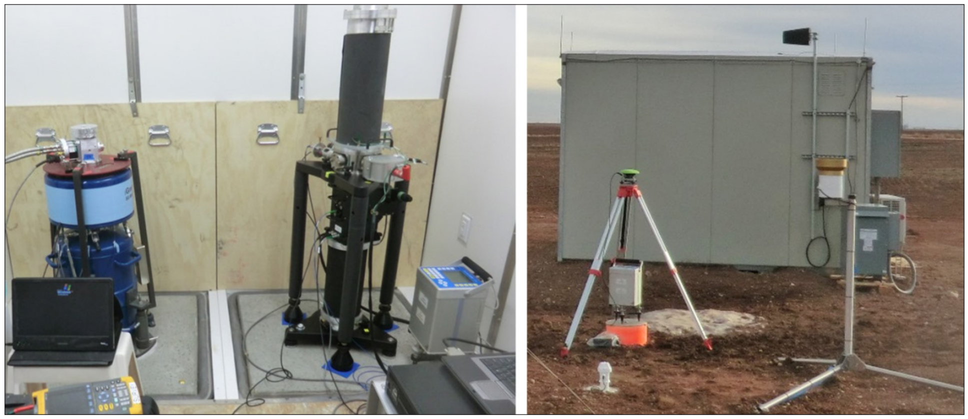

Figure 4. (left): The observation hut and the concrete pillar for GPS measurements. The locations were chosen so that we could secure clear optical paths from a common point to both the GPS pier and the gravimeter piers, through the entry door of the hut. This could allow the pillar elevations to be precisely measured optically. (right): The two concrete pillars for SG and AG measurements are inside the hut. The centers of the two pillars are separated by about 1 m. Three gravimeters, iGrav010 SG, FG5/217 AG and CG5/352 portable gravimeter, were set from left to right..

The iGrav015 SG meter was installed on March 19, 2014. On July 29, 2014 the second SG meter (iGrav017) was installed on a pier adjacent to iGrav015. During the 7-month observation period with iGrav-015 a decrease in gravity of about 20 microGal was observed in the uncorrected residual. Below we present a method for determining whether this signal is real or instrumental. In this analysis, the assumption is first made that iGrav-015 is functioning correctly and that by the time a second SG meter, iGrav-017, is installed, iGrav-015 has negligible drift. By differencing the signals from iGrav-015 and iGrav-017, common mode signals are eliminated allowing a very good fit of the residual to a combination of two exponential functions. In these analysis two exponential functions, Exp1 and Exp2, are calculated and fitted to the residual by eye. The exponential decay constants are assumed to be 2.5 days and 60 days. This function is then subtracted from the "Residual (No Drift Removed)" and presented as the "Drift Corrected Residual". The identical drift

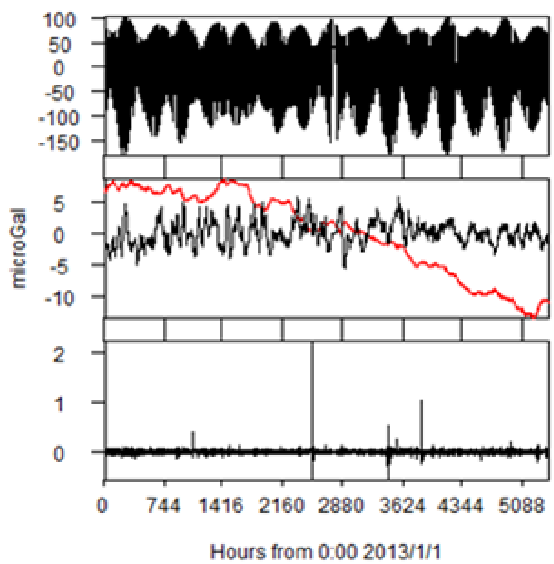

Figure 5. Decomposition of the 225-day continuous gravity data using the BAYTAP-G program into tidal effects (upper panel), trend component (red line in middle panel), response to air pressure (black line in middle panel) and irregularities (lower panel).

Figure 6. Drift analysis by comparison of two SG meters (iGrav-015 and iGrav017). (upper panel): Drift, a combination of two exponential functions, is calculated and fitted to the residual. (middle panel): By differencing the signals from iGrav-015 and iGrav-017, a common mode signals are eliminated allowing a very good fit of the residuals to the drift function. (lower panel): The drift is subtracted from the "Residual (No Drift Removed)" and presented as the "Drift Corrected Residual."

Figure 7. (left): iGFE/CUFE field enclosures installed on a cement pad. (right): iGrav017 SG meter was installed in the iGFE field enclosure.

function, adjusted only for the starting time (t0), is then applied to the entire iGrav-015 time series. The result is examined to see if it is "reasonable". In the final step this same drift function is also subtracted from the iGrav-015 record and presented as "iGrav-015 Drift Corrected Residual" (Figure 6). The parallel record of the two instruments provides a powerful method for discriminating secular changes from instrumental effects even in the absence of a record from an absolute gravity meter.

On December 13, 2014 the iGrav017 was moved to the next observation point, 600m from the previous point, and installed using two protective enclosures (Figure 7). One houses the dewar including the sensor unit, electronics, coldhead and barometer. The other houses the compressor, UPS, and He gas cylinders. Both are climate controlled to maintain the temperature properly.

Discussion

The results presented above show how small gravity changes can be detected by continuous gravity recording with SG meters or gPhone gravimeters. We can detect gravity changes with a resolution of ~ 1 microGal/month using an SG meter, and with a resolution of ~ 1 microGal/day using a gPhone meter. Assuming the validity of a mathematical reservoir model we can estimate gravity changes using a numerical simulator and gravity postprocessor. Then we can infer whether the calculated temporal gravity changes can be detected or not. We discuss detectability in the cases of two geothermal two fields: (1) the Hachijojima island geothermal area, and (2) the Okuaizu geothermal area.

(1) Hachijojima Island Geothermal Field

Generally, existing geothermal simulation models are developed to evaluate geothermal reservoir changes below the cap rock, and do not include the shallower hot spring resources overlying the cap rock. Thus, the detailed simulation of the shallower hot spring resources after the exploitation of the deeper geothermal reservoir has not yet been carried out. Therefore, in FY2010, based on an existing geothermal reservoir model that had been created for reservoir operation of the Hachijojima geothermal power plant, a new numerical model was designed. Ishido *et al.* (2012) carried out numerical simulations of geothermal reservoir systems for two models: a conventional porous-medium model and a MINC model. The study used the STAR general-purpose reservoir simulator with the BRNGAS equation-of-state package which treats three fluid phases (solid NaCl, steam with non-condensable gas, and an aqueous liquid phase) to calculate the evolution of reservoir conditions, and then used the gravity postprocessor to calcu-

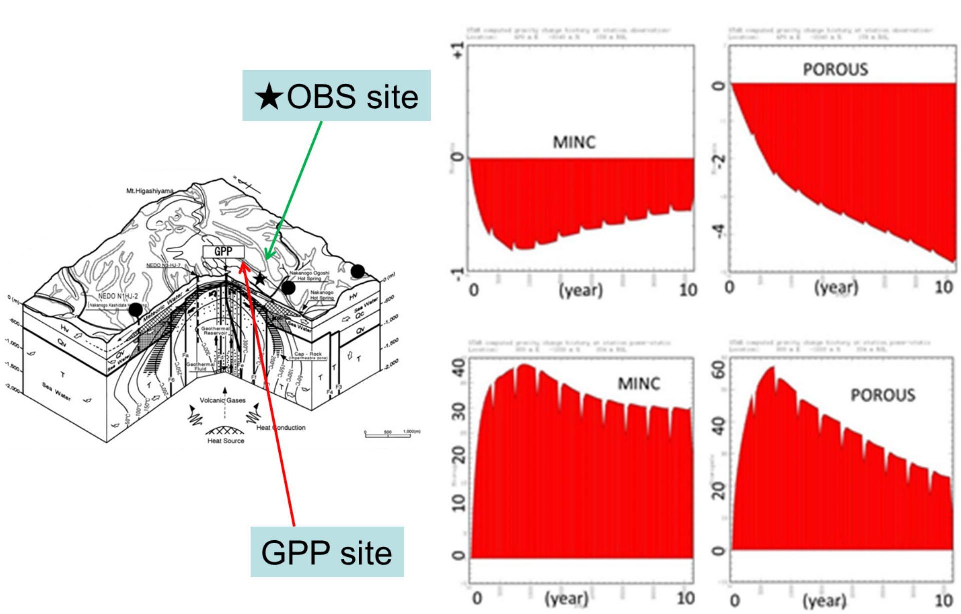

Figure 8. Calculated temporal changes in gravity at the monitoring well (OBS site) and at the injection well (GPP site). Two model cases (MINC model and POROUS model) were calculated.

late the resultant earth-surface temporal microgravity changes at the monitoring well and at the injection well (Figure 8). Long term gravity changes as well as short term changes during the shut-ins associated with periodical maintenance of the power plant were predicted. At the monitoring well the short term changes are too small to detect even if an SG meter is introduced. Long-term changes can be detected with an SG meter. At the injection well short term as well as long term changes can be detected with an SG meter.

(2) Okuaizu Geothermal Field

The Okuaizu geothermal field is located in northeastern Japan. The Yanaizu-Nishiyama geothermal power station commenced operation in May 1995 with 65MW of electrical production (e.g., Saeki, 1999). To appraise the utility of the scheme shown in Figure 2 for geothermal reservoir monitoring, numerical simulations of changes in reservoir conditions due to fluid production and successive geophysical postprocessor calculations were performed based upon a simplified reservoir model (Nishi and Ishido, 2013; Ishido *et al.,* 2015). The main time-variable geophysical observable at the Okuaizu field is not gravity but self-potential (SP). The MINC1 model was selected out of several models through history matching of observed SP change and produced fluid enthalpy. Nishi and Ishido (2012) also calculated temporal variations of gravity at CENTER station by using the geophysical postprocessors (Figure 9). The MINC1 model also reproduces long-wavelength micro-gravity decline between 1997 and 2000. The MINC1 model also suggests small short-term gravity changes associated with the shut-ins. They are observable with an SG meter.

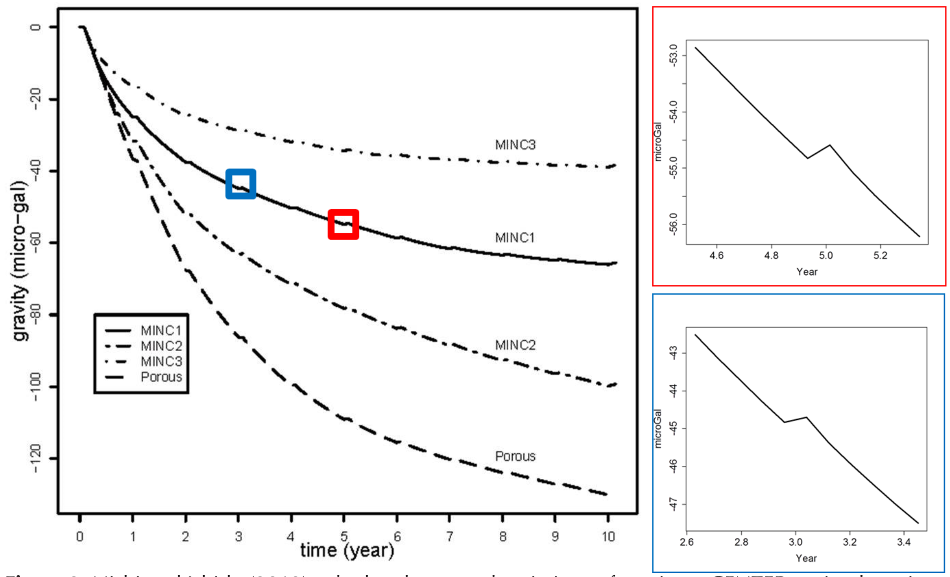

Figure 9. Nishi and Ishido (2012) calculated temporal variations of gravity at CENTER station by using the geophysical postprocessors. The model MINC1 suggests small short-term gravity changes associated with the shut-ins.

Moreover, as a result of hybrid measurements, Sugihara and Ishido (2008) succeeded in delineating the distribution of not only long-term changes for four years but also short-term changes induced by the fieldwide shut-in of production and reinjection wells in the Ogiri geothermal field located in southern Kyushu, Japan. Uncertainty for time-lapse hybrid measurements, however, is larger than instrumental accuracy for FG5. At the Ogiri field fluctuations in survey values are thought to be ±5 microGal, which might be caused by changes in shallow hydrologic conditions. Such uncertainty can be detected using continuous measurements. A combination of the above continuous measurements and reiteration surveys (that is, super-hybrid measurements) can cover a considerable part of the ranges both in time and space. Practical cost/benefit considerations are important as Boedecker (2002) discussed. Generally a user will select from a toolbox of various absolute, relative and SG meters on the basis of cost/benefit considerations to make the best use of limited resources. The super hybrid system is highest not only in benefit but also in cost. If the anticipated short term gravity changes are as small as a few microGals, the SG meter has higher priority than AG meter considering the cost of the two meters (see Longuevergne *et al.,* 2010). If the anticipated gravity changes are as small as one microGal, SG-SG parallel measurements can be the only option.

Conclusions

The data presented here demonstrate that continuous gravity recording with an SG meter is a promising tool for geothermal reservoir monitoring. Continuous microgravity recordings associated with conventional reiteration networks will probably improve monitoring accuracy. By improving the accuracy of observable signals we can attain enough resolution to analyze reservoir properties. It is efficient for improving the resolution to make continuous gravity recordings for the proper period at a few selected stations in and around the network. The observed data would appear to constitute useful constraints for future history-matching studies based on revised models. The initial cost of the super hybrid system is still high, however, the benefit can be commensurateasurant to the cost.

Acknowledgments

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