

Repeat Absolute and Relative Gravity Measurements for Geothermal Reservoir Monitoring in the Ogiri Geothermal Field, Southern Kyushu, Japan

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Abstract. Repeat hybrid microgravity measurements were conducted around the Ogiri Geothermal Field on the western slope of Kirishima volcano, southern Kyushu, Japan. This study was undertaken to detect the short-term gravity change caused by the temporary shutdown of production and reinjection wells for regular maintenance in 2011 and 2013. Repeat microgravity measurements were taken using an A-10 absolute gravimeter (Micro-g LaCoste) and CG-5 gravimeter (Scintrex) before and after regular maintenance. Both instruments had an accuracy of 10 μgal . The gravity stations were established at 27 stations (two stations for absolute measurements and 25 stations for relative measurements). After removal of noise effects (e.g., tidal movement, precipitation, shallow groundwater level changes), the residual gravity changes were subdivided into five types of response. We detected a gravity decrease (up to 20 μgal) in the reinjection area and a gravity increase (up to 30 μgal) in the production area 1 month after the temporary shutdown. Most of the gravity stations recovered after the maintenance. The temporal density changes in the geothermal reservoir were estimated based on these gravity changes.

1. Introduction

Repeat microgravity measurements are used for the assessment of mass balance of ground water and geothermal fluid storage changes. The repeat microgravity measurement has been shown to be an effective method to monitor the balance of production and reinjection in a geothermal reservoir [1, 2, 3]. The production and reinjection of geothermal fluid cause mass movement and redistribution, and these mass changes cause a measurable gravity change on the ground surface. It is possible that the mass balance of the geothermal reservoir could be an index of sustainability of a geothermal power plant.

The results in the previous studies included the gravity change at the reference gravity station, and so the absolute gravimeter was introduced to evaluate this change. The combined absolute and relative gravity measurement is called the hybrid gravity measurement [4], and this type of measurement is applied to volcanological and geothermal monitoring [5, 6].

The Ogiri geothermal power plant (30 MW) is located in the southern part of Kyushu, Japan (Figure 1). Geothermal exploration was started in 1973 with various geophysical surveys and drilling, and operations commenced in 1996. Nittetsu Mining Co., Ltd. operates geothermal steam production, and



Kyushu Electric Power Co., Inc. operates the electric power generation. The production area is located in the eastern part of the geothermal field where the depths of the production wells are about 1000–1500 m. The amount of production is about 10.2 Mt/year, and about 79.5% of production (hot water) is reinjected into the western part of the field [7].

Little research has focused on the short-term gravity changes associated with the shutdown of production and reinjection wells [8]. The present study was undertaken to detect the influence of the shutdown on the production and reinjection of geothermal fluid. Hybrid gravity measurements were collected during the regular maintenance activities in 2011 and 2013. The effect of shallow groundwater level changes is estimated to extract the geothermal reservoir changes. This paper reports the results of the 2013 measurements.

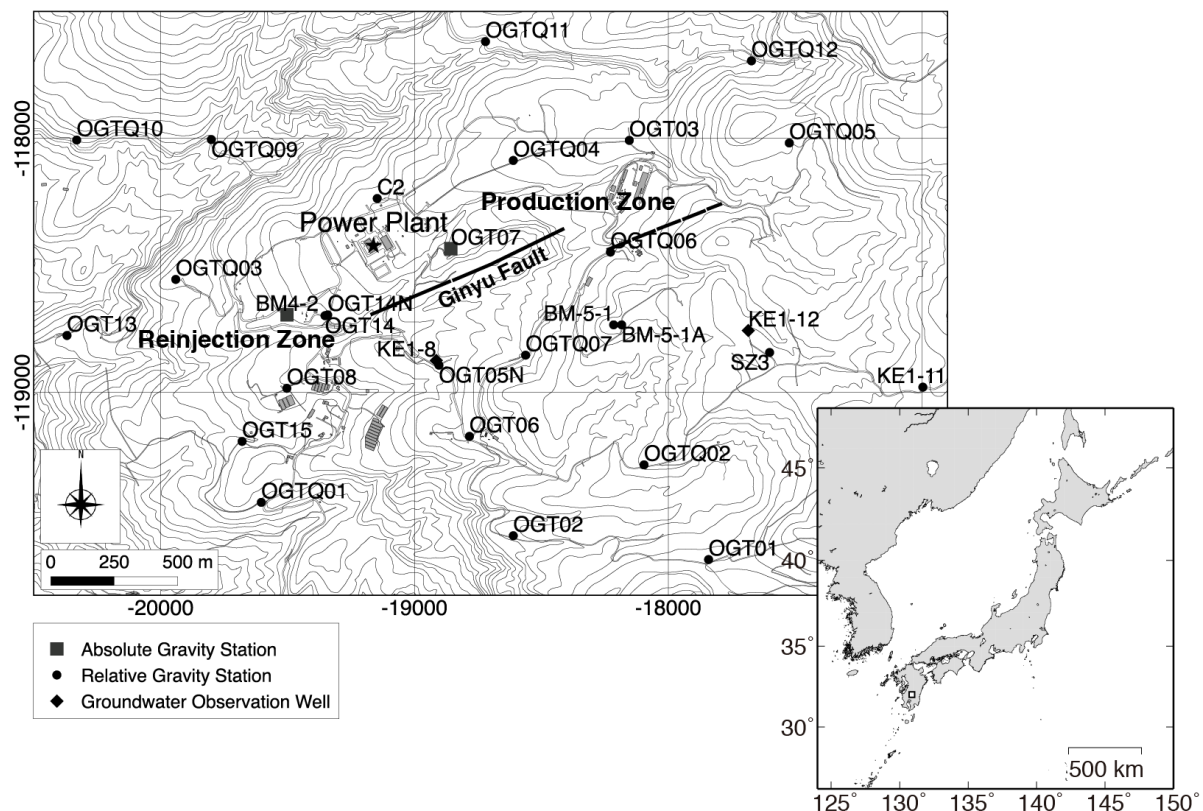


Figure 1. Location of the gravity stations at the Ogiri Geothermal Field, Kagoshima prefecture, Japan. Red circles and green squares show the relative and absolute gravity sampling stations, respectively.

2. Gravity measurement

2.1. Absolute gravity measurement

The A10 is a portable absolute gravimeter manufactured by Micro-g LaCoste Inc. It can operate on a 12-V DC power supply, much like a vehicle battery. The A10 consists of a laser, interferometer, long period inertial isolation device, and an atomic clock to accurately measure the position of the test mass. A test mass is dropped vertically in a vacuum chamber and then allowed to fall an average distance of 7 cm. The raw gravity data are processed with “g” version 9 software, which is designed to work with the Micro-g LaCoste absolute gravimeter to acquire and process gravity data. The software needs the input of some parameters, including the location of the site (latitude, longitude, altitude) and geophysical corrections. We can correct the effect of the tidal movement, ocean load, barometric pressure, and polar motion in acquiring the gravity data [9].

There were two gravity stations for the absolute gravity measurement. The setting of the measurement is shown in Table 1. It took about 30 min for the measurement, and the error of measurements is about 10 μgal .

Table 1. A10 absolute gravimeter settings.

Drop interval	1 sec
Number of drop/set	100 drops
Set interval	6 min
Number of sets	10

2.2. Relative gravity measurement

The relative gravity measurements were conducted using a Scintrex CG-5 gravimeter. Measurements were taken March, April, and May in 2013, at an interval of 1 month. There are 25 gravity stations around the Ogiri geothermal power plant. The two-way measurement method was used to evaluate instrumental drift and precision. The reference station was set at BM 4-2, which monitored the gravity change using an A10 absolute gravimeter. The measured gravity data were reduced to the necessary corrections, such as the earth tide, the height of the instrument, and drift corrections. The earth tidal corrections, including the ocean tidal effect, were calculated using GOTIC2 [10] instead of the instrument's internal program. The errors of each observation were estimated within 10 μgal .

3. Results and discussion

3.1. Absolute gravity changes

Figure 2 shows the results of the absolute gravity measurements from 2011 to 2013. A gravity decrease (up to 19 μgal) was observed just after the regular power plant maintenance in April 2011, in the reinjection area (BM4-2). The gravity recovered by May 2011, and again by May 2013 after the maintenance. These changes seem to reflect the storage change in the reinjection area.

In the production area (OGT-7), small gravity changes were observed just after regular maintenance, but gravity was basically stable from 2011 to 2013.

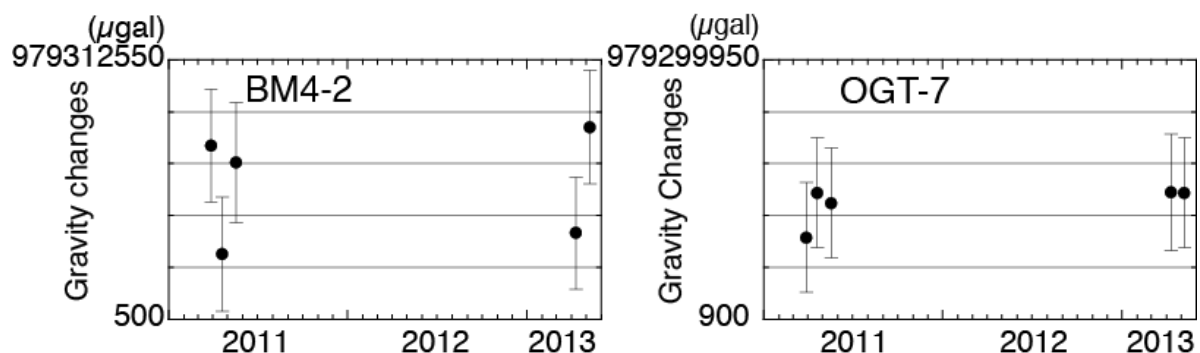


Figure 2. Absolute gravity data at the Ogiri Geothermal Field. BM4-2 is located in the reinjection area, and OGT-7 is located in the production area.

3.2. Effect of shallow ground water level changes

The effect of shallow ground water level changes can be estimated using the equation in Figure 3, assuming an infinite slab aquifer with a porosity of 10%.

The gravity effect that is caused by the ground water level change is estimated using the data from observation wells KE1-8 and KE1-12, shown in Figure 1. Figure 4 shows the ground water level change and converted gravity changes in KE1-8 and KE1-12. The ground water level changes were less than 1

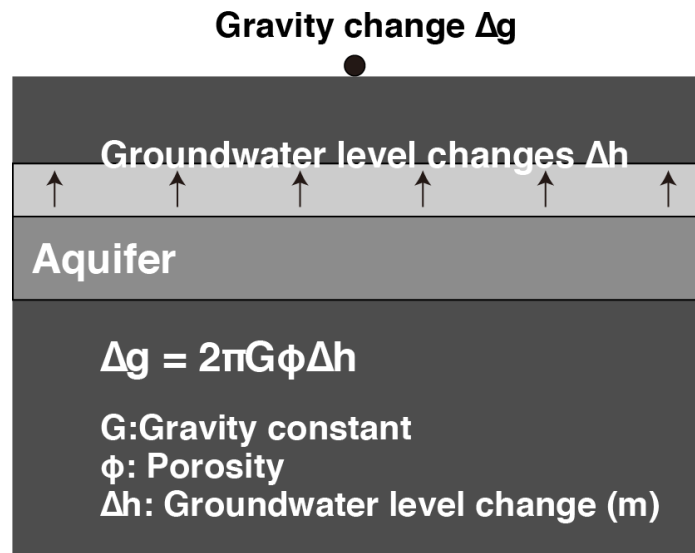


Figure 3. Gravity effect caused by the ground water level change, assuming the infinite slab aquifer.

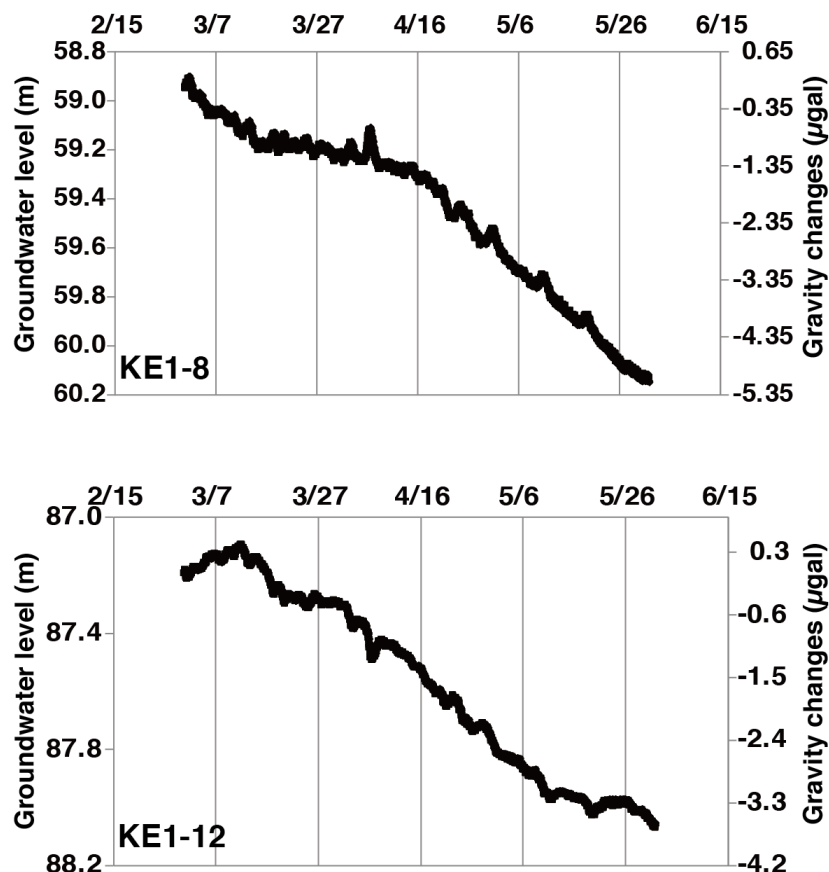


Figure 4. Ground water level changes from the beginning of March to the end of May 2013. The right axis shows the gravity changes converted from ground water level changes.

m during these periods. These water level changes cause about 4 μgal , and the observed gravity changes cancelled out this effect.

The effect of soil water content changes was estimated by GWATER[E] [11], using 10 m-mesh digital elevation maps (DEMs) and the precipitation at the power plant. The estimated result is depicted in Figure 5. Although the effect of this method was less than several μgal , it was calculated at each gravity station and thus removed this effect from the observed gravity changes.

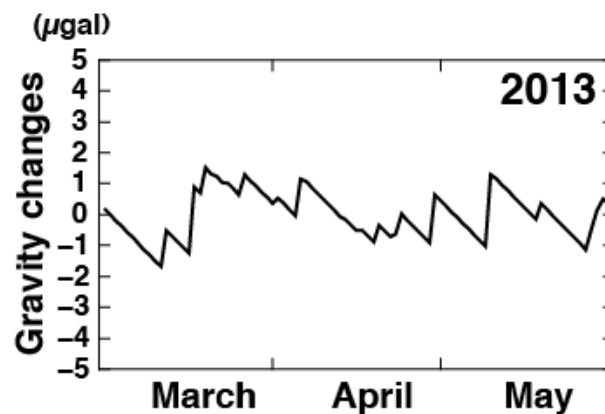


Figure 5. The effect of soil moisture changes from March to May 2013.

3.3. Gravity changes before and after the shutdown of production and reinjection

According to the results of the leveling surveys, the vertical ground movements are less than a few mm/year. Assuming a normal free-air gradient of $-308.6 \mu\text{gal/m}$, ground movement causes less than $3 \mu\text{gal}$. This effect is very small in comparison with the observed gravity change. Consequently, the effect of vertical ground movement is negligible on the observed gravity in the short term.

The residual gravity changes (due to reservoir effects), taken as the difference between the observed and the calculated gravity effect of ground water level changes at each observation station, can be classified into four categories according to the characteristics of the trend (Figure 6). These categories are distributed in three areas as described below.

- Northern and Southern Area (Type A)

This category is situated in the outside of the production and reinjection zone. Although the gravity changes are within $10 \mu\text{gal}$, which is the nominal accuracy announced by the manufacturer, slight gravity changes can be seen before and after maintenance.

- Western Area (Type B and C)

This category is located in the reinjection zone, in the western part of the observation area. Gravity decreases from the onset of stopping the reinjection, and then recovers after restarting the reinjection (Type B). However, the southern area of the reinjection zone kept the low gravity value (Type C).

- Eastern Area (Type D and E)

This category is typical of stations located in the eastern production zone along the Ginyu fault, in the eastern part of the observation area. An increase of residual gravity was seen after the shutdown of the geothermal fluid production, and gravity decrease was observed after production was restarted (Type D). But in the southeastern part of the observation area the high gravity value persisted (Type E).

The data suggest there were increases of residual gravity (up to $30 \mu\text{gal}$) in the production zone and decreases of residual gravity (up to $20 \mu\text{gal}$) in the reinjection zone just after the production and reinjection stopped. Figure 7 shows the contour map of gravity changes from March to April 2013, before and after stopping the production and reinjection in the Ogiri geothermal power plant. The center of residual gravity decrease is located just to the southwestern part of the geothermal field. The center

of this change is located in the western part of Ginyu fault. This gravity decrease indicated the reinjected hot water flowed outside the observation area. In the production area, a gravity increase (up to 30 μgal) was observed in the eastern part of the observation area. These data corresponded to the borehole pressure changes in the reservoir, so this gravity response indicated the recharge came from outside of the observation area.

Figure 8 shows the contour map of gravity changes from April to May 2013. The gravity changes recovered in this period. Some stations still remained at their former level in the southern area of the Ginyu fault. The center of the residual gravity increase is located in the reinjection area of the geothermal field. The gravity decrease is detected in the production area on the Ginyu fault.

These residual gravity changes are consistent with the pressure changes in the geothermal reservoir. Especially for the gravity stations along Ginyu fault, the response of the effect of stopping and restarting of the production and reinjection was quick. Thus, the effects of field operations can be isolated, even for fields with relatively low production rates, like the Ogiri Geothermal Field.

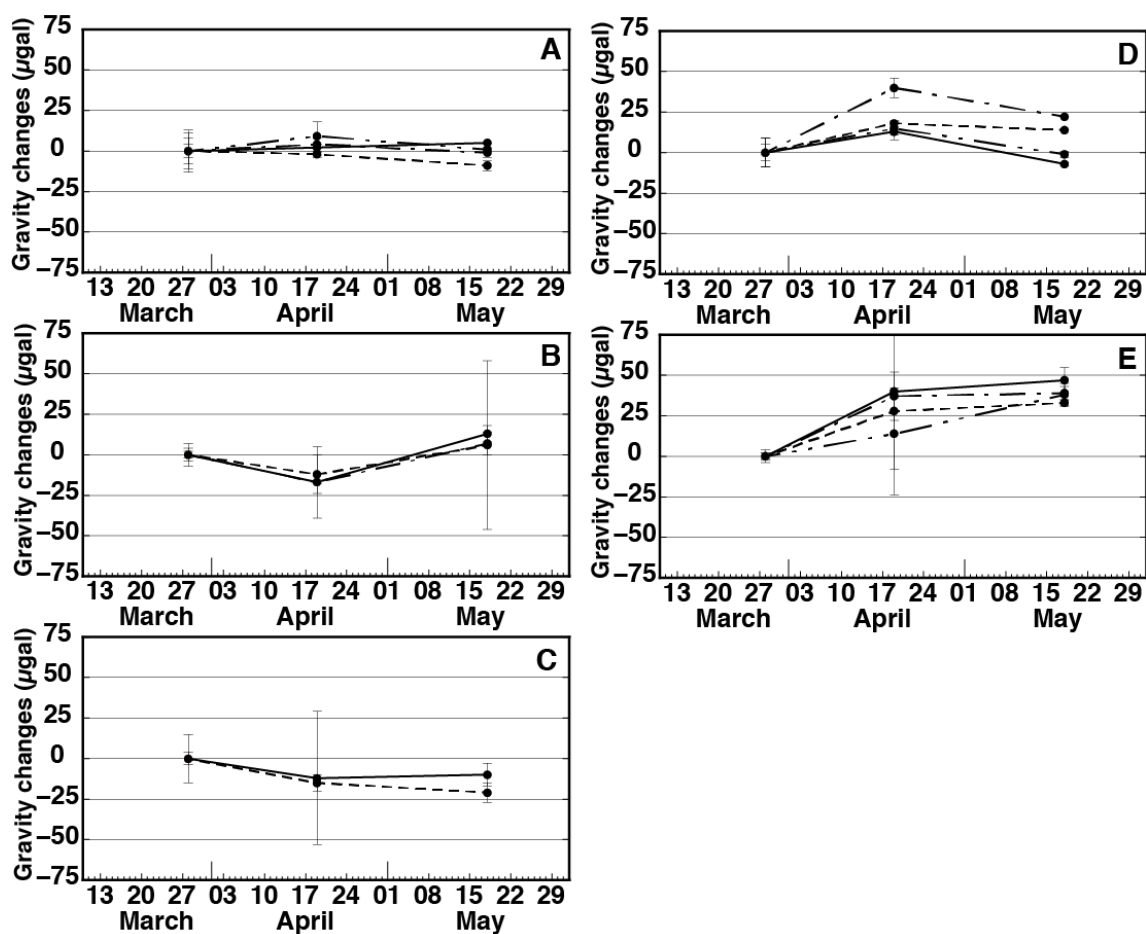


Figure 6. The effect of soil moisture changes from March to May 2013.

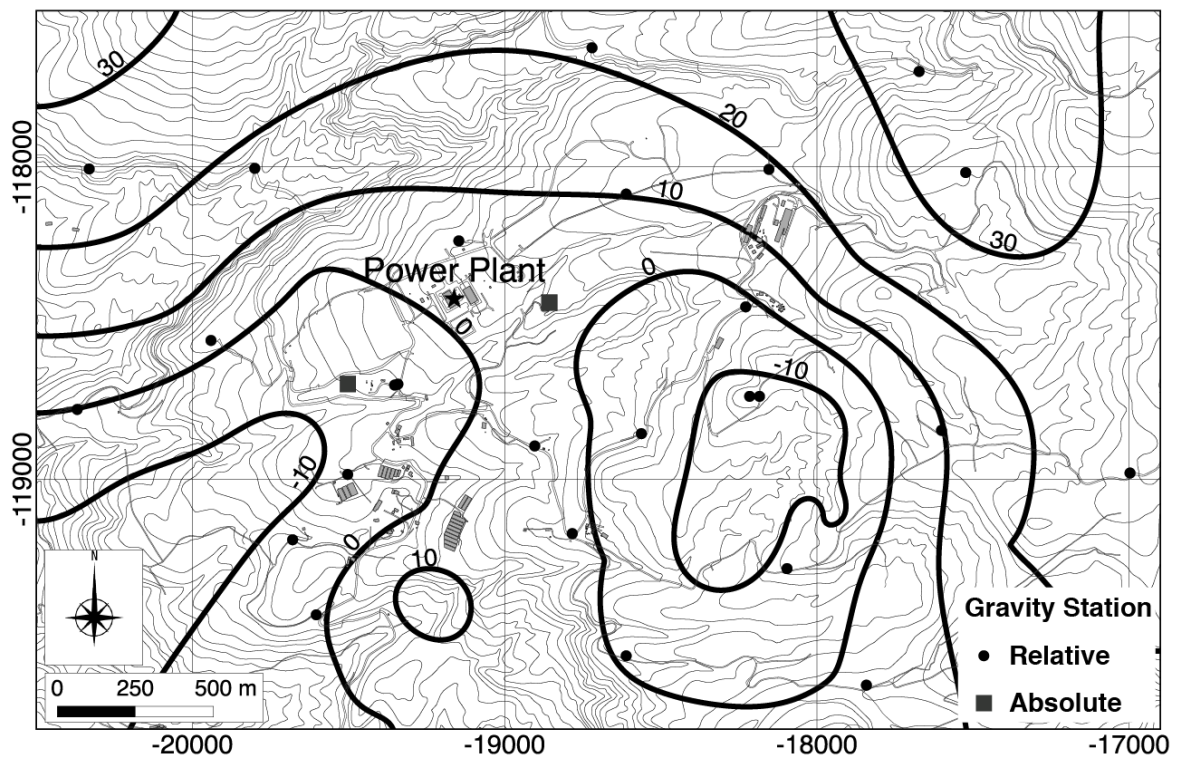


Figure 7. Distribution of gravity changes (μgal) from March to April 2013.

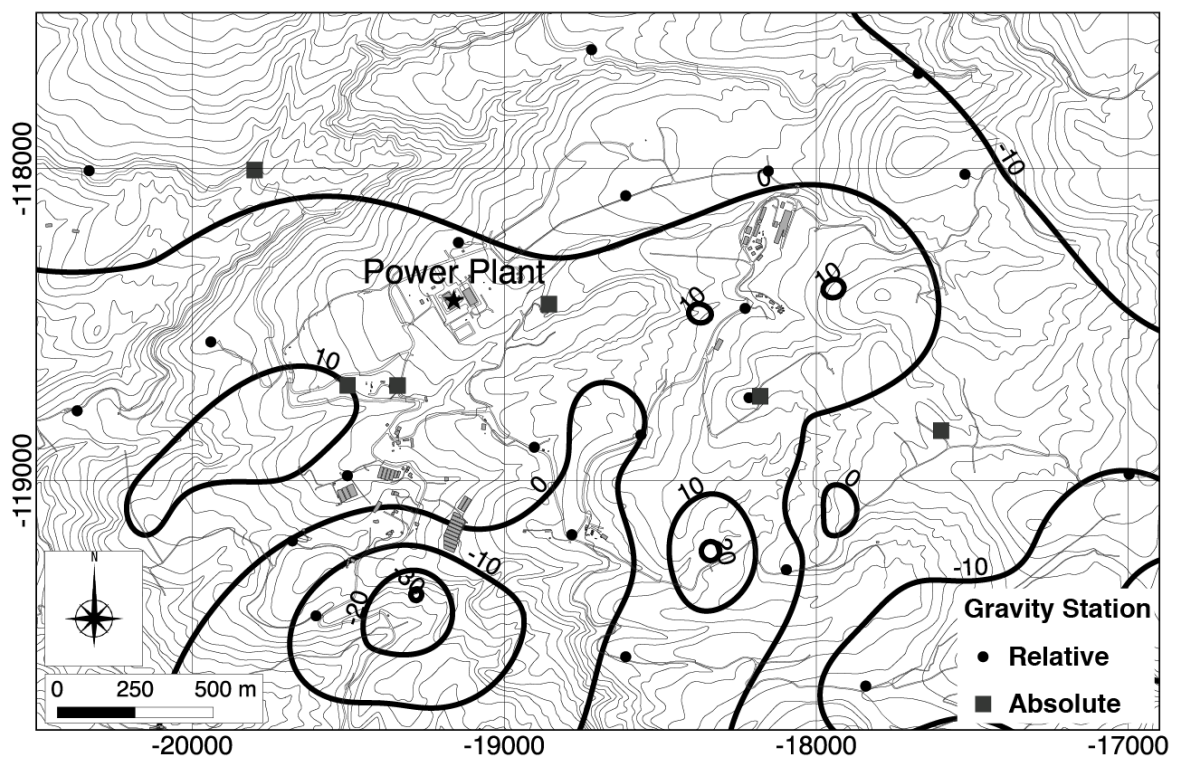


Figure 8. Distribution of gravity changes (μgal) from April to May 2013.

4. Conclusion

Hybrid microgravity monitoring was undertaken to detect the influence of a shutdown on the regular maintenance period around the Ogiri geothermal power plant. Noises that were caused by soil moisture changes and shallow groundwater level changes were removed. Based on these results, residual gravity increases of up to 30 μgal were detected in the production zone, and residual gravity decreases of up to 20 μgal were detected in the reinjection zone. These residual gravity changes are consistent with the changes in the geothermal reservoir. Thus, the effects of field operations can be isolated, even for fields with relatively low production rates, like Ogiri. This study indicates that repeated hybrid gravity measurement is an effective method not only to monitor the long-term mass balance but also to detect short-term reservoir behaviors.

References

- [1] Allis R G and Hunt T M 1986 Analysis of exploitation induced gravity changes at Wairakei geothermal field *Geophysics* **51** pp 1647-1660.
- [2] Nordquist G, Protacio J A P and Acuna A 2004 Precision gravity monitoring of the Bulalo geothermal field, Philippines: Independent checks and constraints on numerical simulation *Geothermics* **33** pp 37–56.
- [3] Nishijima J, Saibi H, Sofyan Y, Shimose S, Fujimitsu Y, Ehara S, Fukuda Y, Hasegawa T and Taniguchi M 2010 Reservoir monitoring using hybrid micro-gravity measurements in the Takigami Geothermal Field, Central Kyushu, Japan *Proceedings World Geothermal Congress 2010*.
- [4] Okubo S, Satomura M, Furuya M, Sun W, Matsumoto S, Ueki S and Watanabe H 2002 Grand design for the hybrid gravity network around the Mt. Fuji volcano *International Symposium on Geodesy, Kanazawa, Abstracts* pp 39–40.
- [5] Furuya M, Okubo S, Sun W, Tanaka Y and Oikawa J 2003 Spatiotemporal gravity changes at Miyakejima volcano, Japan: Caldera collapse, explosive eruptions and magma movement: *Journal of Geophysical Research* **108** pp 1–17.
- [6] Sugihara M and Ishido T 2008 Geothermal reservoir monitoring with a combination of absolute and relative gravimetry *Geophysics* **73** WA37-WA47.
- [7] Thermal and Nuclear Power Engineering Society 2015 The situation and a trend of geothermal power generation 2014 pp 22–23 (in Japanese).
- [8] Nishijima J, Oka D, Higuchi S, Fujimitsu Y, Takayama J and Hiraga N 2015 Repeat microgravity measurements using absolute and relative gravimeters for geothermal reservoir monitoring of the Ogiri Geothermal Power Plant, South Kyushu, Japan *Proceedings World Geothermal Congress 2015*.
- [9] Micro-g LaCoste Inc. 2008 *A10 Portable Gravimeter User's Manual* pp 7-8.
- [10] Matsumoto K, Sato T, Takanezawa T and Ooe M 2001 GOTIC2: A program for computation of oceanic tidal loading effect: *Journal of the Geodetic Society of Japan* **47** pp 243–248.
- [11] Kazama T, Yamamoto K, Fukuda Y and Iguchi M 2014 The importance of hydrological disturbance corrections for relative gravity data: A case study at Sakurajima volcano, southern Kyushu, Japan *Journal of the Geodetic Society of Japan* **60** pp 73-89 (in Japanese with English abstract).