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Reservoir Monitoring Using Hybrid Micro-Gravity Measurements in the Takigami Geothermal Field, Central Kyushu, Japan

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ABSTRACT

Repeated gravity measurements have been applied at the Takigami geothermal power plant in central Kyushu, Japan. We applied a multivariate regression model and removed the effects of shallow groundwater level change in order to extract the gravity change associated with the production and reinjection of geothermal fluids. We used Scintrex CG-3 and CG-3M gravimeters to measure precise gravity change. We detected gravity changes caused by the production and reinjection. However, we cannot assess the gravity change at the reference station, because we only used the relative gravimeter. Hence we introduced the A10 absolute gravimeter (Micro-g LaCoste, Inc) for not only the assessment of the gravity changes at the reference station, but also the detection of the gravity change caused by the underground fluid flow changes.

1. INTRODUCTION

Some procedures are suggested in order to monitor reservoir changes. Micro-gravity measurement is one of the procedures for geothermal reservoir monitoring. The production and reinjection of geothermal fluid causes mass movement and redistributions, which can cause measurable gravity changes on the surface. We can monitor the mass balance, especially the relation between production and recharge, in the geothermal reservoir. Repeated micro-gravity measurements have been carried out in some geothermal fields. Gravity decreased about 1000µgal after 30 years in the Wairakei geothermal field, New Zealand (Allis and Hunt, 1986).

We started repeated micro-gravity measurement before the commencement of Takigami geothermal power plant using Scintrex CG-3 and CG-3M gravimeters to measure precise gravity change (Figure 1). We applied a multivariate regression model and removed the effect of shallow groundwater level change in order to extract the gravity change associated with the production and reinjection of geothermal fluid (Nishijima et al., 2000). We detected gravity decrease and increase in the production and reinjection zone, respectively. These gravity changes are consistent with the changes in mass balance in the geothermal reservoir. This study suggests that repeated gravity measurement is an effective method to monitor geothermal systems.

In a relative gravity measurement, we assumed that the gravity at the reference station does not change. But observed gravity changes include the uncertainty of the reference station, and we cannot separate this uncertainty using relative gravity measurement. Absolute gravimetry can measure the temporal gravity change unequivocally. Hence we introduced the A10 absolute gravimeter (Micro-g LaCoste, Inc) for not only the assessment of the gravity changes at the reference station, but also the detection of the gravity change caused by the underground fluid flow changes. We will report the result of the fluid measurements.

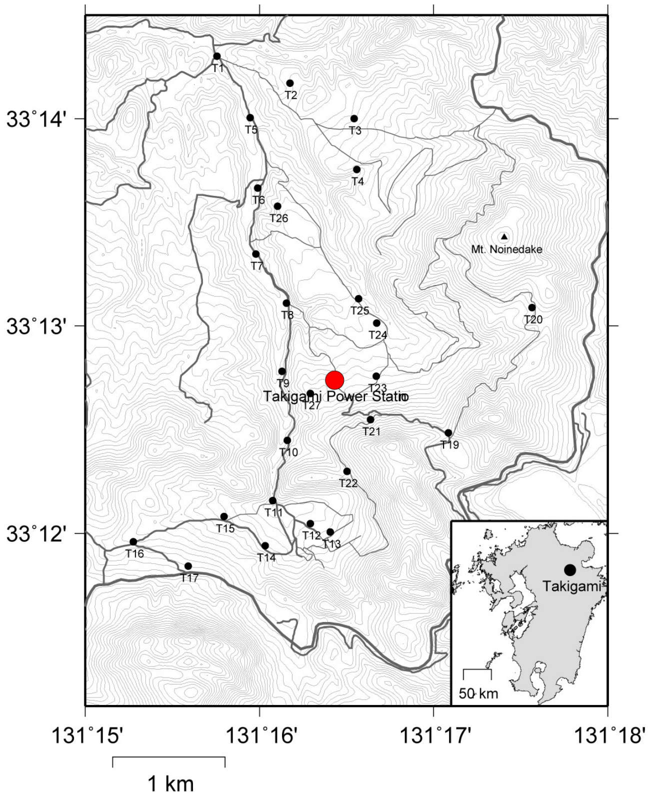

Figure 1: Distribution of observation points (No. 1 to 27) for the repeat gravity measurement at Takigami geothermal field.

2. TAKIGAMI GEOTHERMAL FIELD

Takigami geothermal field is located in the southwestern part of Oita prefecture, central Kyushu, Japan. Geothermal exploration was started in 1979 with various surveys and drilling. The power plant (25MW) was completed in November 1996. The geothermal steam production is conducted by Idemitsu Oita Geothermal Co., Ltd and the electric power generation is conducted by Kyushu Electric Power Co., Inc.

The production area is located in eastern shallow (700-1100m depth) part and western deep (1500-2000m depth) part (Takenaka et al., 1995). The production depth is about 2500m and the reinjection depth from 1000m to 1500m. The amount of production is about 12Mt/year, and about the 85% of production is reinjected to the underground not to cause the ground subsidence.

3. GRAVITY MEASUREMENT

3.1 Relative Gravity Measurement

Repeated gravity measurements have been applied at Takigami geothermal power plant in central Kyushu, Japan. We conducted repeated gravity measurements in May 1991, at 26 observation points. The repeated gravity measurements were conducted in the interval of a few weeks to several months. The two-way measurement method was taken to evaluate the instrumental drift and precision. We estimated the errors of observation as ±10 µgal at each study field.

3.2 Absolute Gravity Measurement

The A10 absolute gravimeter is a portable absolute gravimeter produced by Micro-g LaCoste Inc. It operates on a 12V DC power supply (i.e. vehicle battery). We can measure the absolute gravity using the vehicle battery at the field. The principle of this instrument is simple. A test mass is dropped vertically in a vacuum chamber, and then allowed to fall an average distance of 7 cm. The A10 uses a laser, interferometer, long period inertial isolation device and an atomic clock to measure the position of the test mass very accurately.

The raw gravity data are processed with the software 'g' version 7. This software is designed to work with the Micro-g LaCoste absolute gravimeter to acquire and process the gravity data. And this software needs the input of some parameters, including the location of the site (Latitude, Longitude and Altitude), geophysical corrections, and so on. We can correct the effects of the earth tide, ocean load, barometric pressure and polar motion in acquiring the gravity data.

4. EFFECTS OF SHALLOW GROUNDWATER

It is necessary to estimate the effect of shallow groundwater changes to detect changes in deep geothermal fluid flow by the repeated gravity measurements.

By extending the theory of the autoregressive model (Koike et al., 1995), a multivariate regression model is constructed relating the changes of shallow ground water level to gravity changes:

$$y_t = \sum_{i=0}^{m} \beta_i x_{t-i} + \varepsilon_i$$

where y_t is a response variable, x_t is an explanatory variable with β the coefficient of regression, m is an optimum degree of fit, ε is white noise.

We quantitatively estimated the effect of background gravity change using a precipitation-gravity correlation. Figure 2 shows the comparison between the observed and estimated gravity in the production and reinjection zones.

As a result, the optimum degrees were decided as between three and eight. This means that precipitation exerts the influence on gravity for a period between three and eight months previous to the gravity measurements.

The estimation accuracy of the background gravity is ±10µgal. Before exploitation, there is good agreement between the observed and estimated gravity. However, there are differences up to 40 µgal between observed and estimated gravity just after the commencement of exploitation. The differences in the observed and estimated gravity show the gravity change associated with the production and reinjection of geothermal fluid.

5. RESULT AND DISCUSSIN

5.1 Relative Gravity Measurement

According to the result of leveling surveys, there are vertical ground movements in Takigami geothermal field. These ground movements are less than 1cm/year. Assuming a normal free-air gradient of -308.6µgal/m, ground movement causes less than 3µgal. 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 short term (several years). But we can't assume long-term (more than 10 years) vertical ground movements to be negligible. Therefore we corrected the effect of vertical ground movement using the leveling survey result.

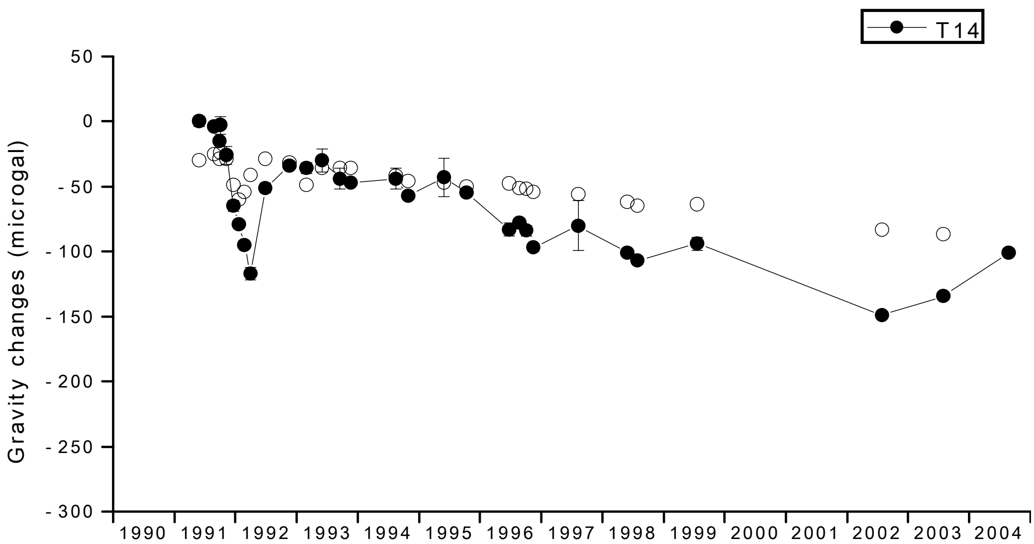

Figure 2: Comparison between the observed and calculated gravity changes at Takigami geothermal field.

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 subdivided into four types of response (Figure 3). The data suggest there were decreases of residual gravity (up to 80 μgal) in the production zone and increases of residual gravity (up to 10 μgal) in the reinjection zone just after the production and reinjection started.

5.1.1 West Area

This group is located along Nogami river, and gravity changes are small compared with other groups. As soon as the production and reinjection of the geothermal fluid begins a slight decrease of the residual gravity is seen. Gravity decreases from July 1999 until July 2002, and then starts increasing.

5.1.2 Southwest Area

This group of response is seen at observation points located in the production zone along the Teradoko fault, in the southwestern part of the observation area. Gravity decreases from the onset of production until July 2002, and then starts increasing.

5.1.3 East Area

This group of response is typical of stations located in the eastern production zone along the Noine fault, in the eastern part of the observation area. A decrease of residual gravity was seen immediately after the geothermal fluid production started, and between June and August 1996 gravity increased sharply. After that, residual gravity gradually increased.

Figure 4 shows the contour map of gravity changes from 1996 to 1997 just after the commencement of Takigami geothermal power plant. The center of residual gravity decrease is located just to the south of the power plant. The center of this change is located in the basin structure. The mass movement associated with the production of the geothermal fluid occurred in the basin structure.

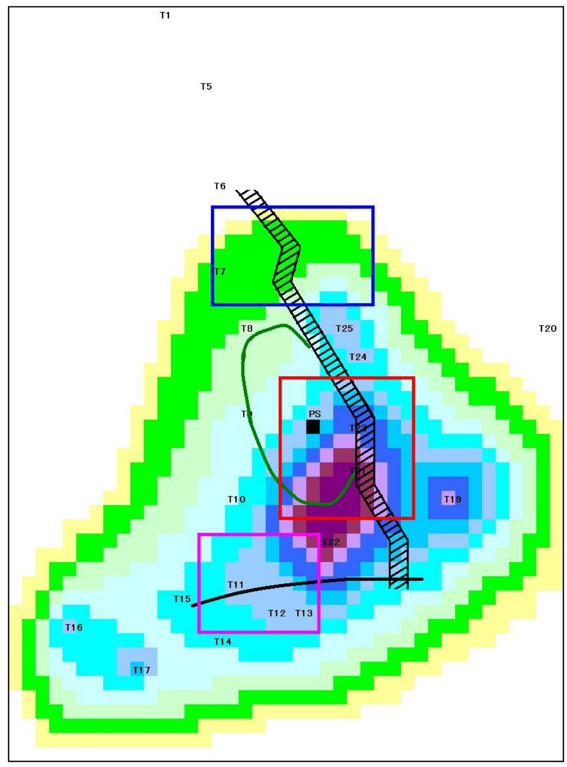

Figure 4: Distribution of gravity changes from 1996 to 1997.

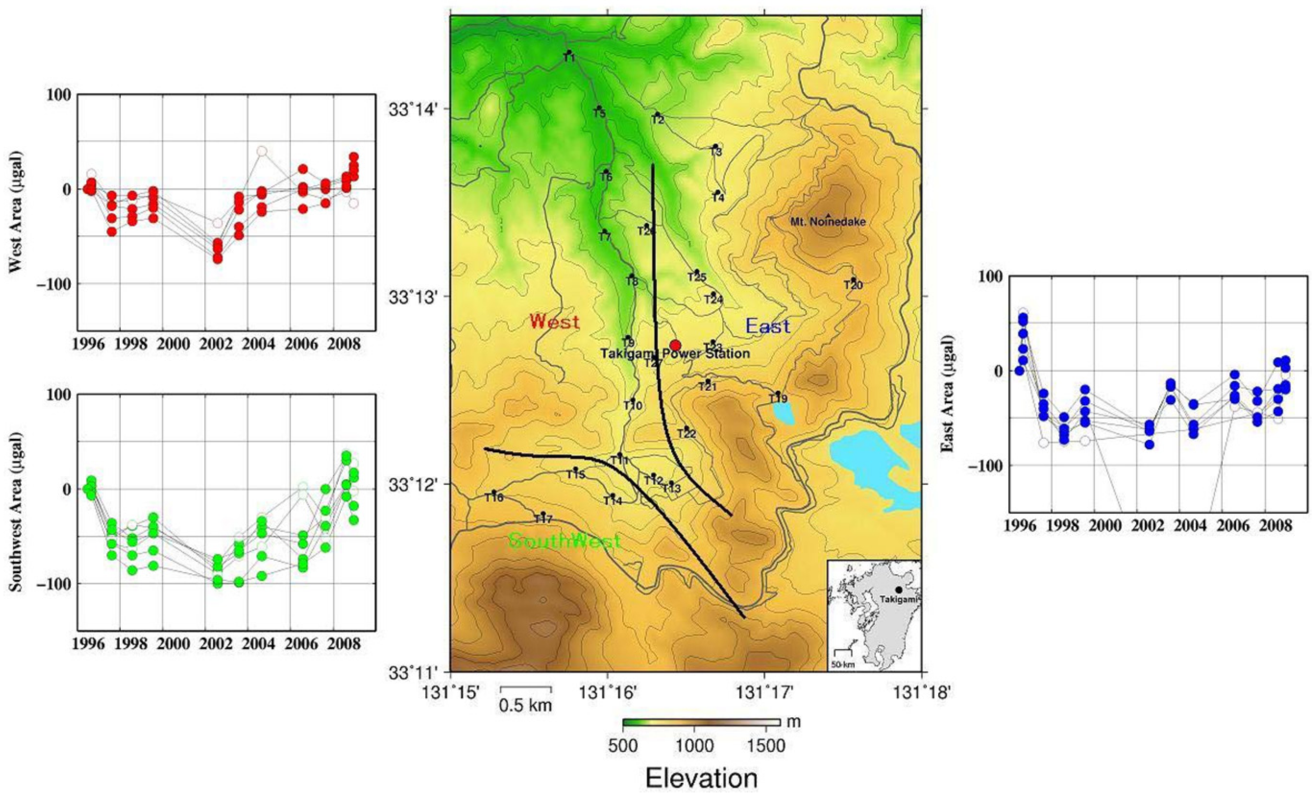

Figure 3: Distribution of typical patterns of residual gravity changes in the Takigami geothermal field.

Figure 5 shows the contour map of gravity changes from 2003 to 2007. The gravity changes recovered in this period. Some stations reached their former level. The center of residual gravity increase is located in the southwestern part of the power plant. It seems like the recharge of geothermal fluid comes from southwestern part of the field

These residual gravity changes are consistent with the changes in mass balance in the geothermal reservoir. Thus, the effects of field operations can be isolated, even for fields with relatively low production rates like the Takigami geothermal field.

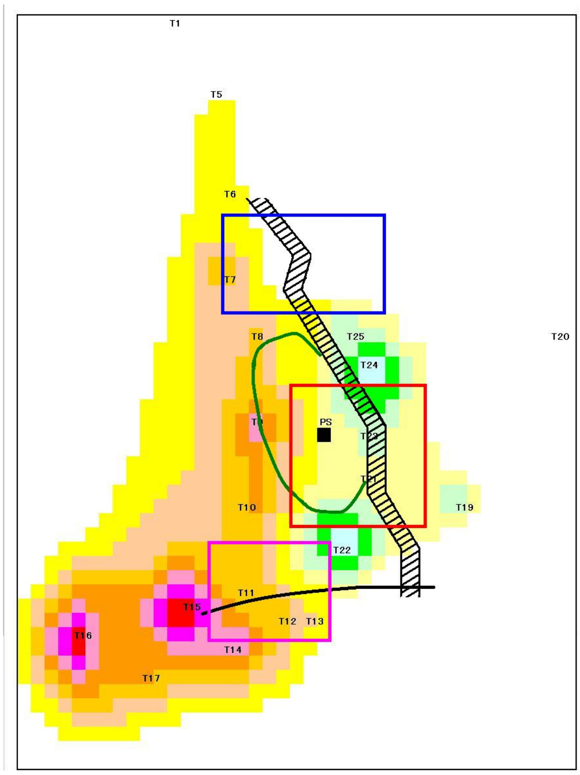

Figure 5: Distribution of gravity changes from 2003 to 2007.

Application of Gauss's Potential Theorem (La Fehr, 1965) to gravity changes gives a quantitative estimate of the mass changes. We based our changes on the contour map of the gravity (Figure 4 and Figure 5).

Figure 6 shows the mass balance from 1996 to 1997 just after the commencement of Takigami geothermal power plant. Mass decrease determined by gravity change from 1996 to 1997 is 8.83 Mt. The total discharge, difference between produced (10.53 Mt) and reinjected (8.53 Mt) mass, was 2.0 Mt. The difference between the total discharge and the mass decrease is thought to be a natural mass recharge (-6.83Mt) from the surrounding area. The negative natural mass recharge indicates that the production of geothermal fluid exceeds the recharge from the surrounding area.

Figure 7 shows the mass balance from 2003 to 2007. In this period, Mass decrease determined by gravity change is 0.48 Mt. The total discharge, difference between produced (11.44 Mt) and reinjected (10.11 Mt) mass, was 1.78 Mt. The difference between the total discharge and the mass decrease is thought to be a natural mass recharge (2.26Mt) from the surrounding area. This estimation suggests that a large amount of the geothermal fluid was recharged and underground fluid flow is reaching a new equilibrium state.

This study suggests that repeated gravity measurement is an effective method to monitor geothermal reservoirs.

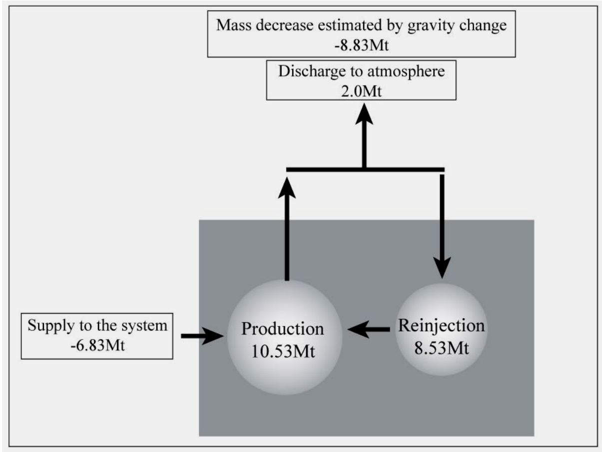

Figure 6: Mass balance based on the contour map of gravity changes at Takigami geothermal field from 1996 to 1997.

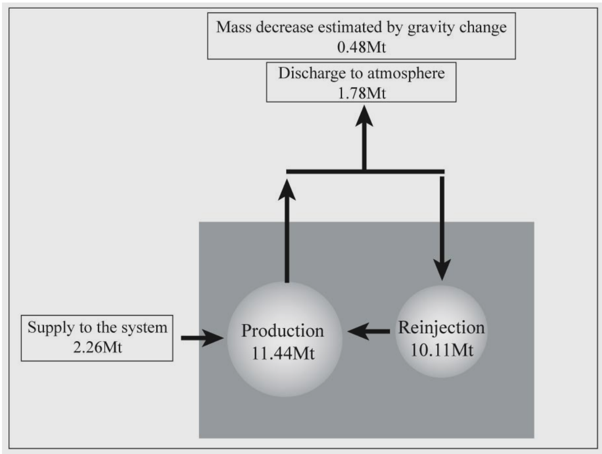

Figure 7: Mass balance based on the contour map of gravity changes at Takigami geothermal field rom 2003 to 2007.

5.2 Absolute Gravity Measurement

We chose the 4 stations (T13, T22, T26 and T27) to conduct the repeated gravity measurement using a vehicle battery. We conducted absolute gravity measurement three times (Feb., Apr. and Dec., 2008). A regular repair was carried out on April 2008. Production and reinjection were interrupted in this period. We tried to detect the influence of stopping the production and reinjection of geothermal fluid.

The obtained gravity data is combined into a set which usually consist of 100-150 drops. Our typical setup parameters are listed below:

Drop interval	:	1 second
Number of drops/set	:	100
Set interval	:	2 minutes
Number of set	:	10

Figure 8 shows the result of absolute gravity measurement. We observed gravity decrease just after the regular repair in the reinjection zone (T26A). After that the gravity recovered in December. These changes seem to be caused by the change of reinjection. On the other hand, we did not detect the gravity change just after the regular repair in the production zone (T27A). But we detect the gravity decrease at the all stations located in the production zone. In the T26A, the gravity changes are very small (less than 20 μgal) compared with the production area. This station seems well suited to be the reference station for the relative gravity. But we don't have data from the rainy season. We will then measure the absolute gravity in a rainy season.

6. CONCLUSION

We started repeated gravity measurements about 5 years ago before the beginning production and reinjection at the Takigami geothermal field. Based on these result, we estimated the background gravity change that is caused by seasonal changes of shallow ground water level by using a multivariate regression model relating gravity to precipitation. As a result, we were able to decide the background gravity change with an accuracy of ±20μgal. We can use the correlation to eliminate the effects of background gravity change. Residual gravity increases of up to 10 μgal were detected in the reinjection zone, and residual gravity decreases of up to 40 μgal were detected in the production zone. These residual gravity changes are consistent with the changes in mass balance in the geothermal reservoir. Thus, the effects of field operations can be isolated, even for fields with relatively low production rates like Takigami. This study suggests that repeated gravity measurement is an effective method to monitor geothermal reservoirs.

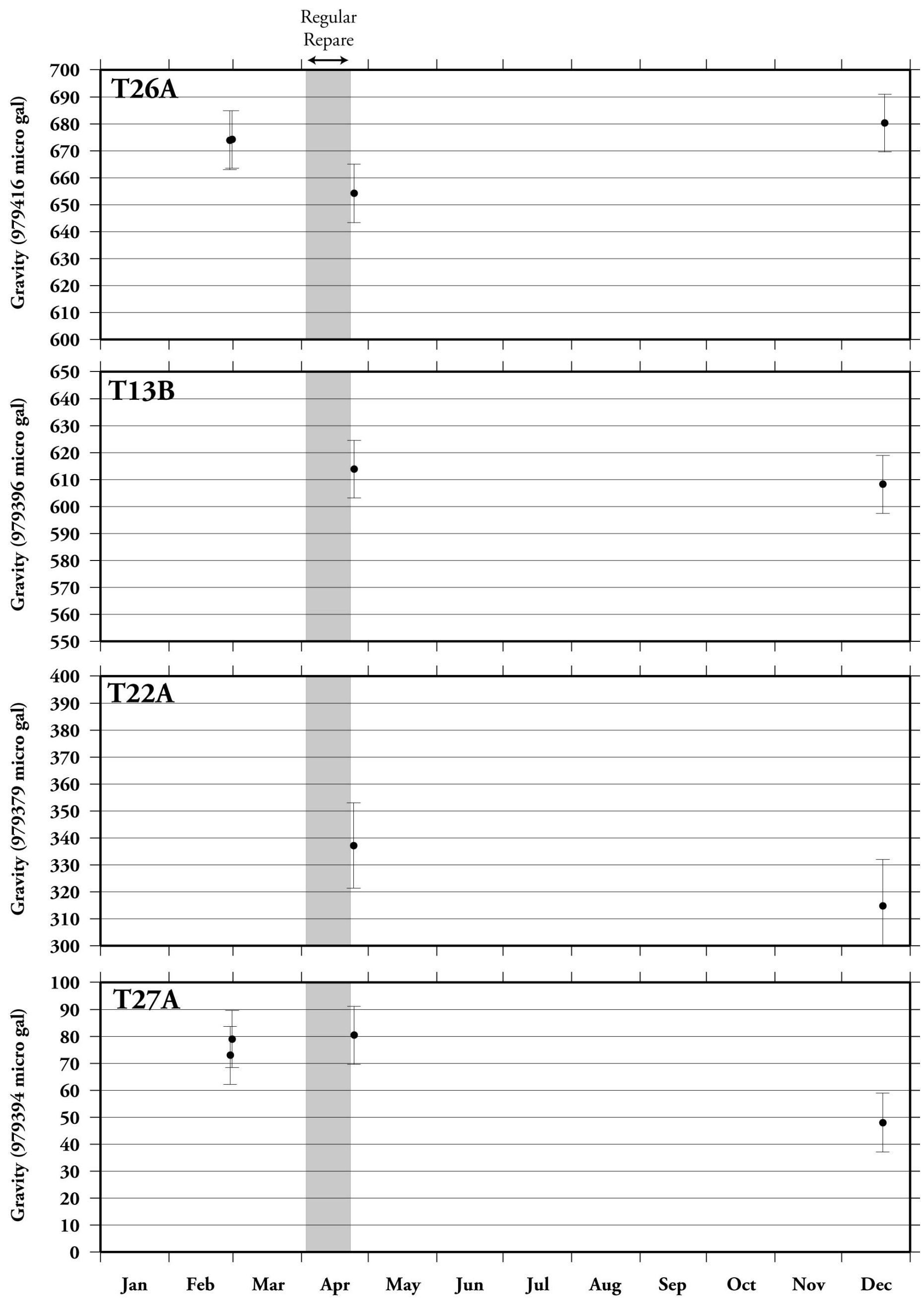

Figure 8: Absolute gravity data at the Takigami geothermal field. T26A is located in the reinjection zone, the others is located in the production zone.

REFERENCES

Allis, R. G. and Hunt, T. M.: Analysis of exploitation induced gravity changes at Wairakei geothermal field. Geophysics, Vol. 51, (1986), pp.1647-1660.

Koike, K., Doi, E. and Ohmi, M.: Seasonal fluctuations and analysis of ground-water level using multivariate regression model, Geoinformatics, 2, (1991), 255-263.

La Fehr, T. R.: The estimation of the total amount of anomalous mass by Gauss's Theorem, Jour. Geophys. Res., Vol. 70, (1965),1911-1919.

Micro-g LaCoste Inc. A10 Portable Gravimeter User's Manual, (2006) , 7.

Nishijima, J., Shimosako, N., Motoyama, T., Fujimitsu, Y., Ehara, S., Ikeda, K., Akasaka, C., Furuya, S., Gotoh, H., and Motomatsu, T.: Gravity Monitoring of Geothermal Reservoirs in the Takigami Geothermal Field, Central Kyushu, Japan - Gravity Changes Caused by Production and Reinjection of Geothermal Fluids - , Journal of the Geothermal Research Society of Japan, 22, (2000), 117-130.

Takenaka, T., Gotoh, H., Yamamoto, Y. and Furuya, S.: Exploration and development of the Takigami geothermal system, Kyushu, Japan, Journal of the Society of Resource Geology, 45, (1995), 361-376 (in Japanese with English abstract).