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GEOTHERMAL FLUID FLOW MONITORING BY THE REPEAT GRAVITY MEASUREMENT AT THE TAKIGAMI GEOTHERMAL FIELD, JAPAN -APPLICATION OF HYBRID GRAVITY MEASUREMENT BY AN ABSOLUTE GRAVIMETER (A10) AND RELATIVE GRAVIMETERS (CG-3M AND CG-5)-

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ABSTRACT

It is important to understand the geothermal reservoir behavior in order to produce geothermal fluid for a long time. The mass changes at subsurface with production and reinjection of geothermal fluid cause the gravity changes on the surface. Repeat gravity measurements have been applied at the Takigami geothermal field in Central Kyushu, Japan, where the Takigami power plant has been generating since November 1996. We used a Scintrex CG-3, CG-3M and CG-5 relative gravimeters in order to measure gravity change caused by production and reinjection of geothermal fluid, but we could not estimate the gravity change at the reference station. To solve this problem, we introduced an A10 absolute gravimeter (Micro-g LaCoste, Inc.). In addition, the A10 was used for not only the assessment of the gravity changes at the reference station, but also the detection of the gravity change caused by the subsurface fluid mass changes at some other measurement stations. However, it was impossible that the A10 absolute gravimeter was applied at all of the stations, because the condition of the measurement was strict. Therefore we have applied the relative gravimeters in such strict situations. Thus both absolute and relative gravimeters can complement each other.

We have measured the gravity repeatedly since the commencement of power generation at the Takigami geothermal power plant, and we have detected the gravity changes which were consistent with the changes in mass balance in the geothermal reservoir. As a result, we inferred that the current fluid mass in the Takigami geothermal field has recovered to as much as that before production and reinjection had started. The absolute gravity measurement was able to evaluate the gravity change at the reference station, but the application of the hybrid measurement was effective because the condition of the absolute gravity measurement was strict.

INTRODUCTION

When the geothermal power plant starts electricity generation, various surveys are conducted in the geothermal area in order to monitor the geothermal reservoir behavior. Micro-gravity measurement is one of the methods for geothermal reservoir monitoring. The production of geothermal fluid and the reinjection of hot water cause mass changes and redistributions, which can cause measurable gravity changes on the ground surface. We could estimate the mass balance, especially relation between production and recharge, in the geothermal reservoir.

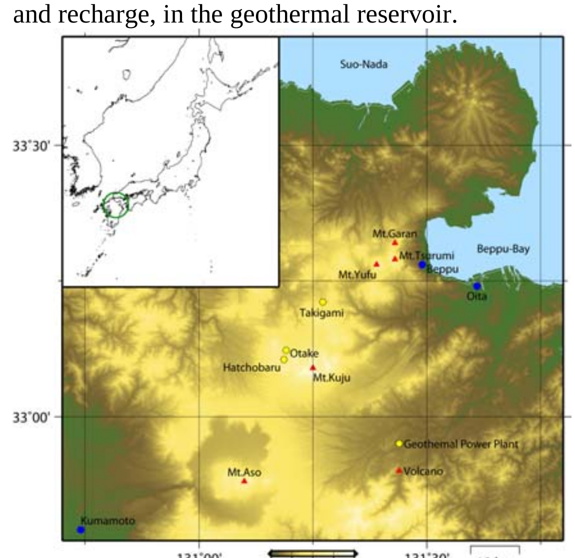

Figure 1: Map of the Hohi geothermal region, northeast Kyushu, showing the location of the Takigami area, the major Quaternary volcanoes and the Otake-Hatchobaru geothermal area.

We have conducted repeat micro-gravity measurement in the Takigami area using Scintrex CG-3 and CG-3M relative gravimeters before the commencement of Takigami geothermal power plant. We detected gravity changes in the both production and reinjection areas. These gravity changes are consistent with the changes in mass balance in the geothermal reservoir. This study suggests that repeat gravity measurement is an effective method to monitor geothermal systems.

But we could not estimate the gravity changes at the reference station (T1), because we only used the relative gravimeters. Hence we introduced the A10 absolute gravimeter (Micro-g LaCoste, Inc.) from 2008 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 movement.

TAKIGAMI GEOTHERMAL AREA

Takigami geothermal area is located in the southwestern part of Oita prefecture, the Hohi geothermal region in the northeast of the Kyushu island, southwest Japan (Figure 1). This is one of the most active geothermal regions in Japan. In the Hohi geothermal region, there are many geothermal manifestations such as fumaroles and hot springs at the surface. Although the Takigami area lies within the Hohi geothermal region, this area is regarded as a concealed geothermal area because there are no geothermal manifestations at the surface. Geothermal exploration was started in 1979 with various surveys and drilling. 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 power plant (25MW) was completed in November 1996.

The production area is located in eastern shallow (700-1,100m depth) part and western deep (1,500-2,000m depth) part (Takenaka et al., 1995). The reinjection depth is from 1,000m to 1,500m. The amount of production is about 12 Mt/year, and about 85% of the production is reinjected to the underground in order not to cause the ground subsidence. The reinjection area is located in the northern part of the Takigami geothermal power plant.

Here is the summary of the geologic structure in the Takigami area. In the eastern side of the Takigami geothermal power plant, Noine fault lies. And in the south side of the Takigami geothermal power plant, there are Teradoko fault and a few E-W faults (Figure 2). The Takigami geothermal power plant lies on the basin-like structure (Furuya et al., 2000).

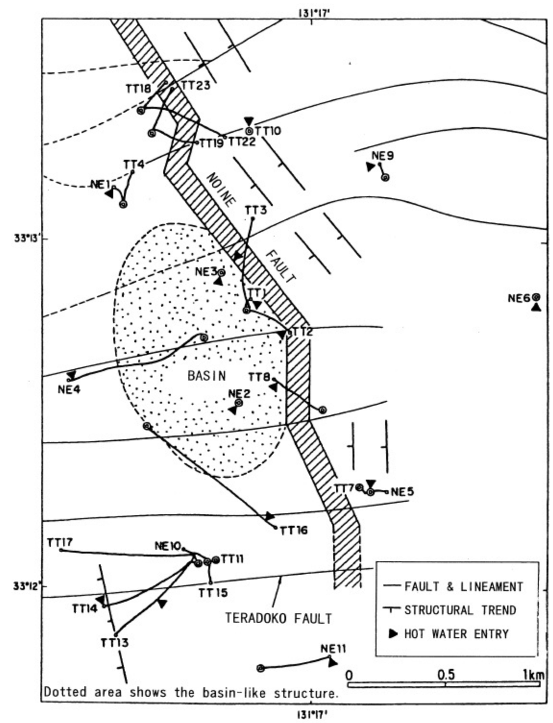

Figure 2: Conceptual geologic structure of the Takigami area. The traces of wells and faults, and the locations of hot water entries to thewells are shown (Furuya et al., 2000)

GRAVITY MEASUREMENT

Relative gravity measurement

The repeat gravity measurements were conducted at intervals of a few weeks to several months using the relative gravimeters. Repeat relative gravity measurements have conducted at 26 stations (Figure 3). The two-way measurement method was taken to evaluate the instrumental drift and precision because the gravity values obtained from the gravity measurement are very small. We estimated the errors of observation as ±10 μgal at each study field.

We corrected the effect of vertical ground movement using the leveling survey result. The residual gravity changes (due to reservoir effects) can be subdivided into three types of response (Figure 4).

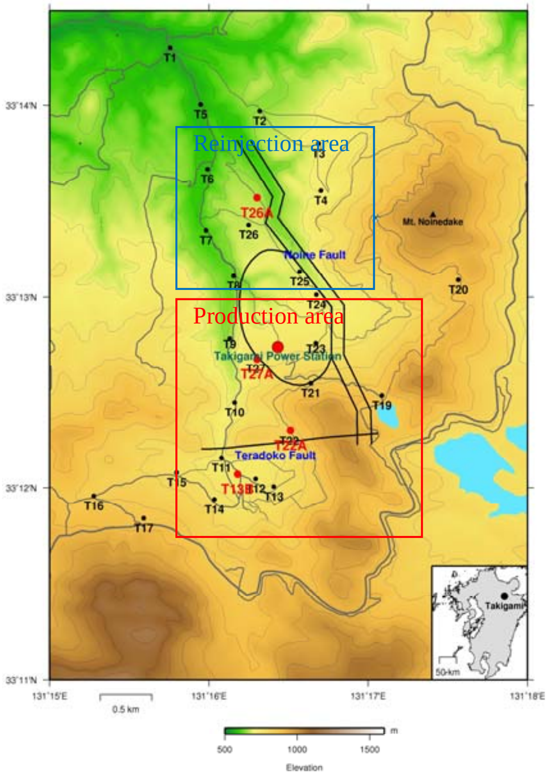

Figure 3: Topographic map of this study area. Small black circles show the distribution of the observation stations (T1 to T27) for the relative gravity measurement, middle black circles show four gravity stations (T-13B, T-22A, T-26A and T-27A) for the absolute gravity measurement and large red circle shows the Takigami geothermal power plant. Broadly speaking, the north side of the power plant is reinjection area, and the south side is production area.

Western area

This group is located along Nogami River. As soon as the production of the geothermal fluid and reinjection of hot water began, a slight decrease of the residual gravity occurred. Gravity decreased from July 1999 until July 2002, and then started increasing. The gravity changes are calm compared with other groups.

Southwestern area

This group of response is seen at the observation stations located in the production zone along the Teradoko fault, in the southwestern part of the observation area. Gravity decreased from the onset of production until July 2002, especially the large residual gravity decreases (more than 50 μgal) occurred in the first year after the production of the geothermal fluids had begun, and then started increasing.

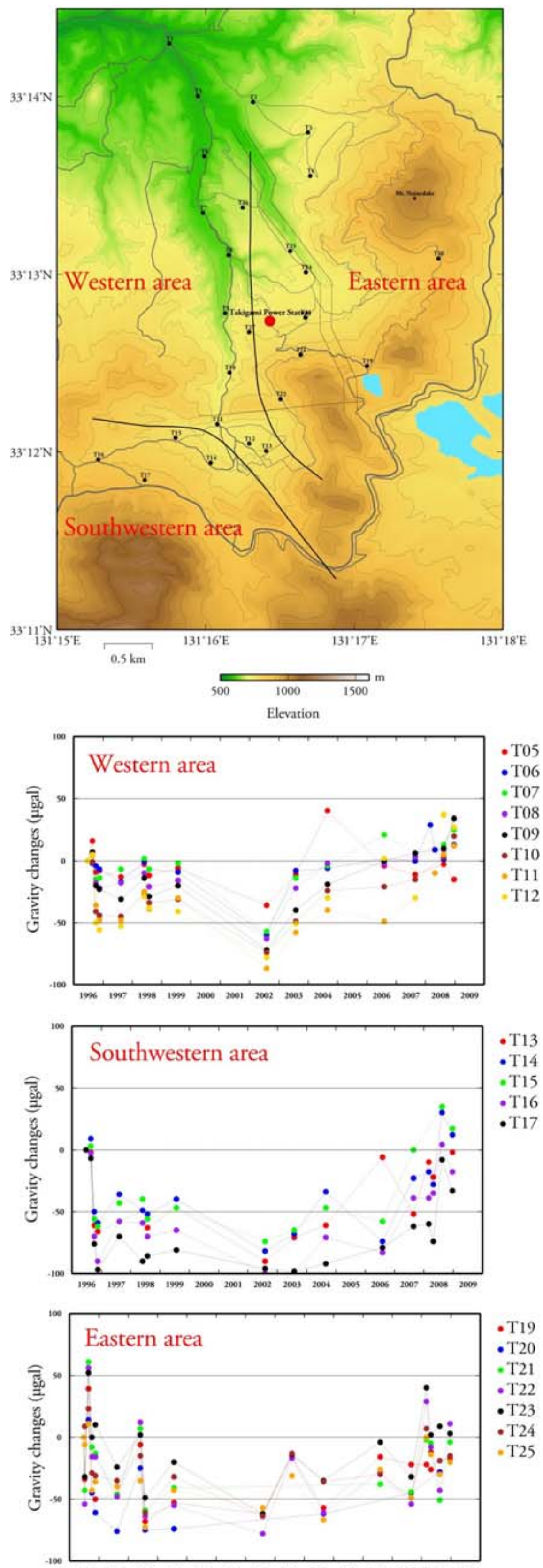

Figure 4: Distribution of typical patterns of residual gravity changes in the Takigami geothermal field.

Eastern area

This group of response is typical of the 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. Until 2002, the residual gravity decrease occurred. After that, residual gravity gradually increased.

According to the results of leveling surveys, there are small vertical ground movements in the Takigami geothermal field. These ground movements are less than 1cm/year. Assuming a normal free-air gradient (-308.6µgal/m), ground movement causes less than 3µgal. This effect of this vertical ground movement 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 cannot disregard the effect of the vertical ground movement, if the observation continues long-term, such as more than 10 years. Therefore we corrected the effect of the vertical ground movement using the leveling survey results.

As results of the repeat relative gravity measurements, the residual gravity in the entire observation field has been recovered as much level as the gravity before the production and reinjection of the geothermal fluids.

Hybrid gravity measurement using absolute and relative gravimeters

We monitored the behavior of the Takigami geothermal reservoir by the repeat relative gravity measurements. However, we could not estimate the gravity changes at the reference station.

The absolute gravity measurement has some merit. Because the observed gravity data at each measurement is separated, the systematic error in the relative gravity measurement is hard to be detected. Hence reference station is not necessary. On the other hand, the absolute gravity measurement has some demerit. An absolute gravimeter is four or five times as expensive as a relative gravimeter. Larger area in order to set a gravimeter than relative gravimeters is necessary. It also took long survey period. The AC-powered battery was necessary.

We consider that the survey so as to complement the demerit of both relative and absolute gravity measurements is necessary, and so we determined to introduce the hybrid gravity measurement by absolute and relative gravimeters.

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. The principle of this instrument is simple. A test mass is dropped vertically in a vacuum chamber with an average fall length 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 obtained gravity data is combined into a set which usually consists of 100-150 drops.

The raw gravity data are processed with the software 'g' version 7. 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 effect of the earth tide, ocean load, barometric pressure and polar motion in acquiring the gravity data.

We selected the 4 stations (T-13B, T-22A, T-26A and T-27A) in order to conduct the repeated gravity measurement using some 12 V lead batteries. T-26A is located in the reinjection zone, the others are located in the production zone. We conducted the absolute gravity measurements three times from February 2008 to November 2009. A regular maintenance in the Takigami geothermal power plant was carried out in April 2008. Production and reinjection were interrupted in this period. We started the absolute gravity measurement just before the maintenance, in order to try to detect the influence of stopping the production and reinjection of geothermal fluid.

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 5 shows the result of absolute gravity measurement. We observed gravity decrease (19 µgal) just after the maintenance in the reinjection zone in T-26A. After that the gravity recovered in December, 2008. These changes seem to be caused by stop of reinjection. On the other hand, we detected small gravity increase (4.4 µgal) just after the maintenance in the production zone (T-27A).

After the maintenance, the gravity changes are small in almost all stations, except in case of December 2008 at T-27A. These stations seem to be suitable as reference stations for the relative gravity measurement. We will then measure the absolute gravity in a rainy season in order to confirm the effect of the seasonal groundwater level changes.

A large gravity change (more than 50 μgal) was observed in T-27A from the end of April 2008 to June 2009. There are some factors causes the gravity changes: the station elevation change, seasonal changes of shallow groundwater, the influence of the maintenance, and others.

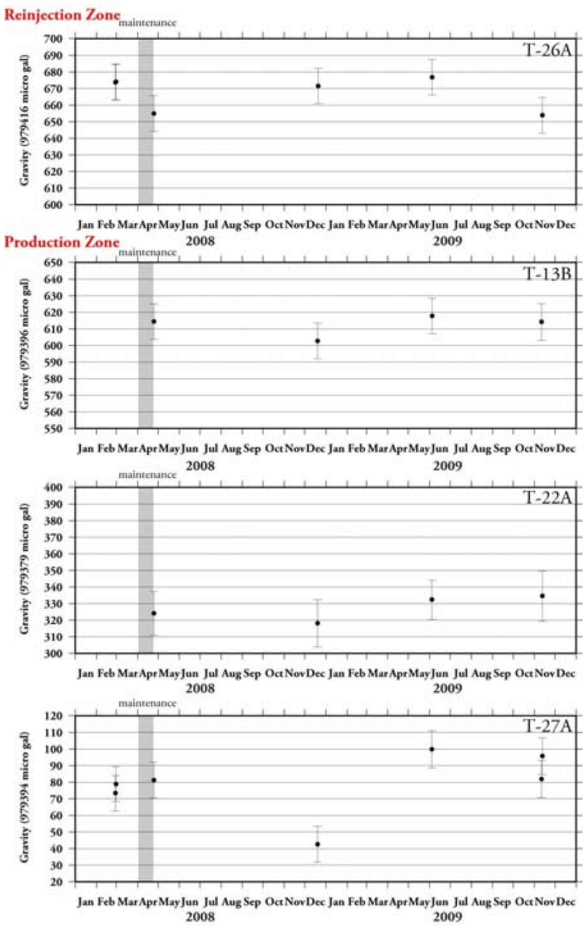

Figure 5: Variation in absolute gravity (μgal) from 2008 to 2009 at Takigami geothermal field. T-26A lies in the reinjection area and others lie in the production area.

DISCUSSION

Gravity change in the reinjection area

As a result of the absolute gravity measurement, the gravity in the production area has not changed much, while the gravity change in the reinjection area during the regular maintenance is -19μgal. When the reinjection into the geothermal reservoir is stopped, the geothermal fluid escapes from this reinjection area. We consider the reduction of the obtained gravity data indicates this mass loss. According to Okabe (1979), we can calculate mass drained from the reinjection area by using equation (1). We assumed the reinjection area as the rectangular prism (800m × 300 m × 270m) (Figure 6). As a result of the calculation, 0.6 Mt geothermal fluids escaped from the reinjection area during about 20 days. This value becomes 1,260 t/h when we convert this value per time. Because the average quantity of hot water reinjected into the geothermal reservoir is 1,100 t/h, it may be said that this result is proper. Consequently, we conclude that the gravity change at T-26A indicates the mass change in the reinjection area.

$$g = -G\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk}\left[x_i \ln\left(y_j + r_{ijk}\right) + y_j \ln\left(x_i + r_{ijk}\right) + 2z_k \arctan\frac{x_i + y_j + r_{ijk}}{z_k}\right] \quad (1)$$

g: Gravity which the rectangular affect to the observation point [m/s^2]
G: Gravitational constant (6.673×10^{-11} m^3/kg s^2)
ρ: Porosity difference between the rectangular and neighboring rocks

$$r_{ijk} = \sqrt{x_i + y_j + z_k}$$

$$\mu_{ijk} = (-1)^i (-1)^j (-1)^k$$

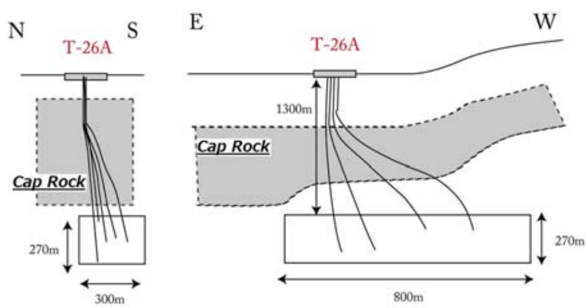

Figure 6: A conceptual model for the calculation based on the gravity change in the reinjection area.

Gravity change at reference station based on the gravity at T26A

Station T1 is the reference station for the relative gravity measurement. We want to measure the absolute gravity at T1, but T1 has little area enough for us to put the absolute gravimeter A10, so we could not obtain the absolute gravity at T1. Therefore we estimate the gravity at T1 based on the absolute gravity data at T-26A (Figure 7).

The gravity change at T1 lies in the range of about 10μgal. So we consider that T1 is proper for the reference station.

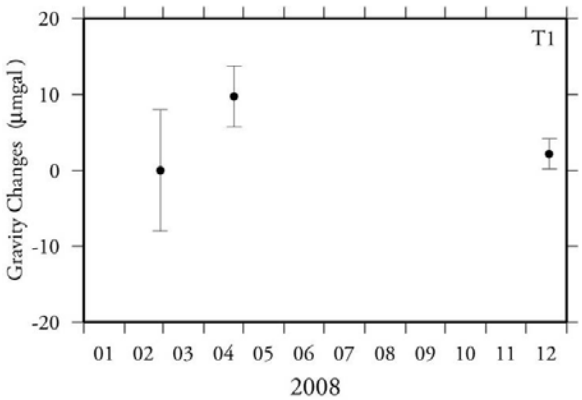

Figure 7: Relative gravity change at T1 (the reference station for relative gravity measurement) based on the absolute gravity at T-26A.

CONCLUSION

We have conducted the repeat relative gravity measurements for about 15 years in the Takigami geothermal field. We estimated that the gravity of the entire observation field in Takigami geothermal field has recovered as much as the gravity before onset of the power generation. In order to give this results more reasonable, we introduced the absolute gravity measurement. As a result of the absolute gravity measurement, we figured that the reference station T1 for the relative gravity measurements is appropriate. At T-26A in the reinjection area, we obtained the gravity changes that were caused by stopping production of geothermal fluid during the regular maintenance in the Takigami geothermal power plant. This study can suggest the hybrid gravity measurement of relative and absolute gravimeters is useful for recognizing the behavior of the geothermal reservoir.

ACKNOWLEDGEMENT

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