PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

EVALUATION OF GEOTHERMAL RESERVOIR MASS CHANGE FROM THE GRAVITY CHANGE AT THE TAKIGAMI GEOTHERMAL AREA, OITA PREFECTURE, JAPAN

Daisuke Oka[1], Yasuhiro Fujimitsu[1], Jun Nishijima[1], Yoichi Fukuda[2] and Makoto Taniguchi[3]

[1]Kyushu University, [2]Kyoto University, [3]RIHN
744 Motooka Nishi-ku
Fukuoka, 819-0395, Japan
e-mail: daisuke-oka@mine.kyushu-u.ac.jp

ABSTRACT

In Takigami geothermal area, we have continued the geothermal reservoir monitoring by using gravity change from 1991, in order to monitor the mass transfer caused by production and reinjection of geothermal fluid. We, however, had measured only relative gravity measurements by using relative gravimeters (SCINTREX CG-3, CG-3M and CG-5), so we haven't been able to evaluate the gravity change at the reference station of the relative gravity measurements. Therefore, we introduced an A10 absolute gravimeter (Micro-g LaCoste, Inc.) in 2008. We used the A10 gravimeter for not only the assessment of the gravity changes at the reference station, but also the detection of the absolute gravity change caused by the subsurface fluid mass changes at some other measurement stations.

As a result of absolute gravity measurements, the gravity change at the reference station of the relative gravity measurements is small enough for this evaluation, within about 10 µgal. So we estimated that this reference station is appropriate for the relative gravity measurements. Because we judged that the gravity change detected by the relative and absolute gravity measurements illustrated the mass transfer in the geothermal reservoir, we divided the Takigami geothermal area into 3 areas from the pattern of the gravity change after the commencement of the Takigami geothermal power plant, and we estimated the 4 stages of geothermal fluid flow pattern from temporal gravity change. Based on these classifications, we led a conceptual reservoir model of the Takigami geothermal area.

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. It is important to understand the geothermal reservoir behavior in order to produce geothermal fluid for a long time. In addition, it is necessary to consider the influence on environment because the production of a large quantity of geothermal fluid and the reinjection of a large quantity of water are performed in the geothermal area. 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.

Figure 1: Hybrid gravity measurement by using the A10 absolute gravimeter (left) and the CG-5 relative gravimeter (right)

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 could estimate the mass balance, especially relation between production and recharge, in the geothermal reservoir.

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 an 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 (Figure 1).

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 2). 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.

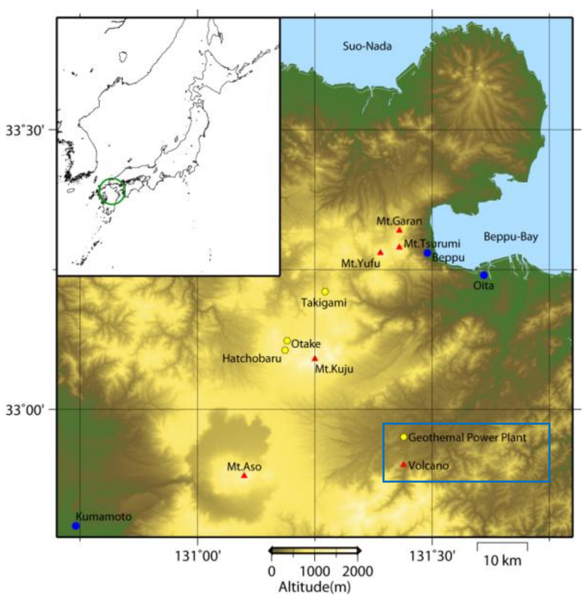

Figure 2: Map of the Hohi geothermal region, northeast Kyushu, showing the location of the Takigami area, the major Quaternary volcanoes and the Otake-Hatchobaru geothermal area.

Geothermal exploration in Takigami 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, and its produced power has been increased to 27.5MW since June 2010.

The production area is located in the eastern shallow (700-1,100m depth) part and the 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 3). The Takigami geothermal power plant lies on the basin-like structure. It is considered that these faults and the basin-like structure form the geothermal reservoir (Furuya et al., 2000).

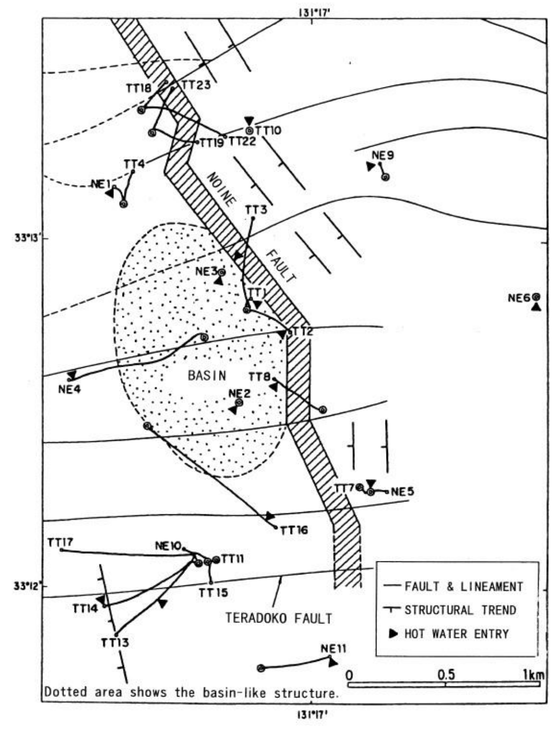

Figure 3: Conceptual geologic structure of the Takigami area. The traces of wells and faults, and the locations of hot water entries to the wells are shown (Furuya et al., 2000)

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 4). 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 5).

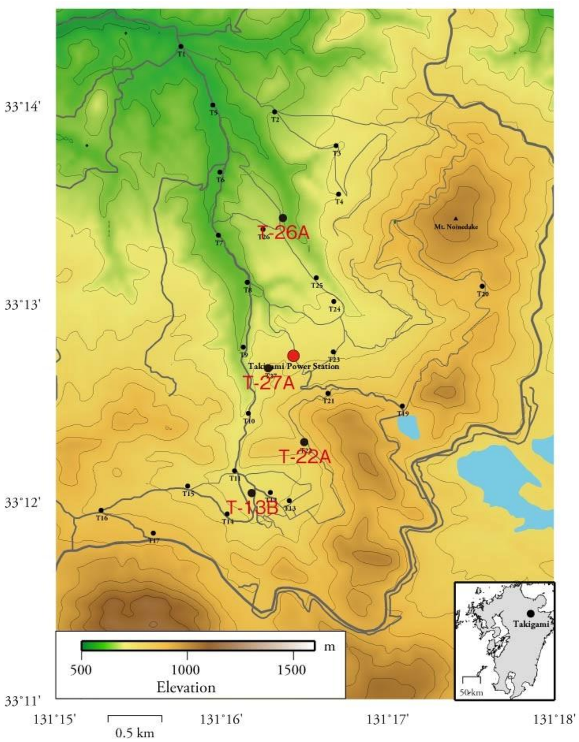

Figure 4: Topographic map of this study area. Small black circles show the distribution of the observation stations (T1 to T27) for the relative gravity measurement, middle black circles show four gravity stations (T-13B, T-22A, T-26A and T-27A) for the absolute gravity measurement and large red circle 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.

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 area. 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.

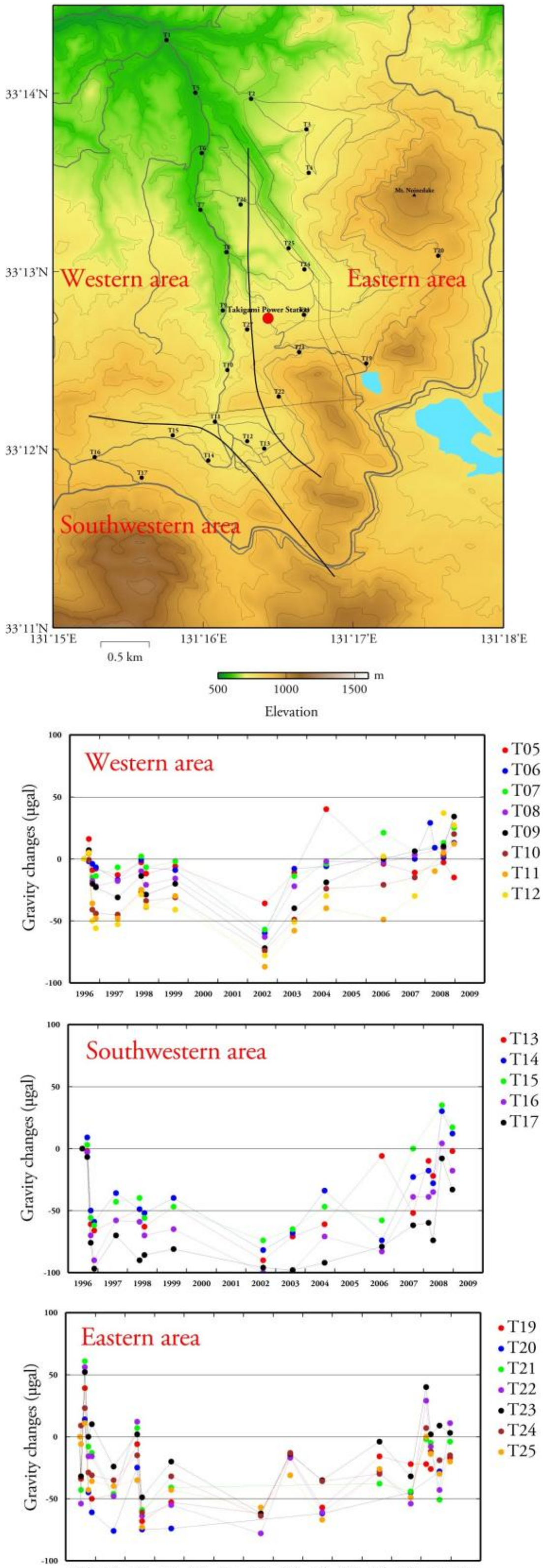

Figure 5: Distribution of typical patterns of residual gravity changes in the Takigami geothermal area.

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 for the relative gravity measurement. In order to estimate it, it is necessary that the absolute gravity measurement is introduced at the reference station.

The absolute gravity measurement has some merit. Because the observed gravity data at each measurement is separated, the systematic error shown in the relative gravity measurement is hardly incident. Hence the 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. In case of conventional absolute gravimeters like FG-5 (Micro-g LaCoste, Inc.), the AC-power supply is 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

We have introduced an A10 absolute gravimeter since 2008. The A10 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 (Figure 4). 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 6 shows the result of absolute gravity measurement. We observed gravity decrease (19 μgal) just after the maintenance in 2008 at T-26A on the reinjection zone. At T-26A, the gravity change is small. On the other hand, we detected small gravity increase at the stations which are in the production area. These gravity increases in the production zone seem to be suitable for the result of the relative gravity measurement.

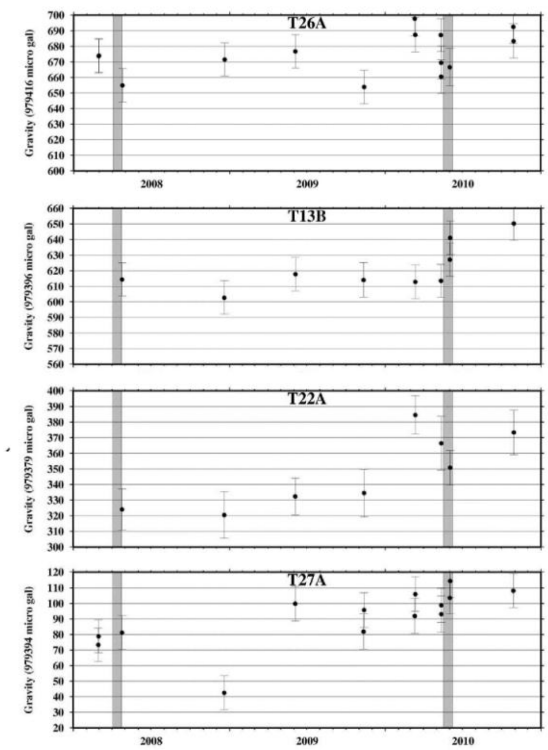

Figure 6: Variation in absolute gravity (μgal) from 2008 to 2010 at theTakigami geothermal area. T-26A lies in the reinjection area and others lie in the production area. Gray ties show the periods of regular maintenances in the Takigami geothermal power plant.

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. It's small and the reference station for the relative gravity measurement is appropriate. So we judged that the relative gravity measurement for this study area is appropriate.

.

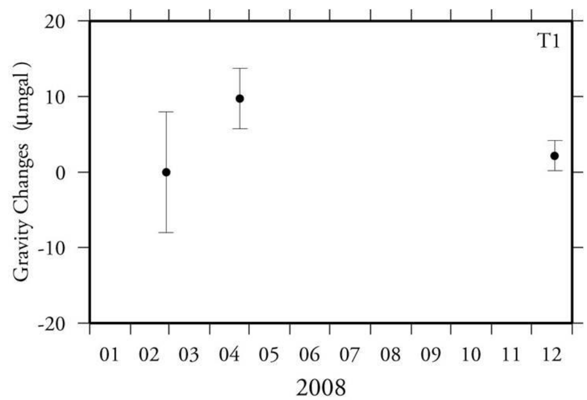

Figure 7: Relative gravity change at T1 (the reference station for relative gravity measurement) based on the absolute gravity at T-26A.

MASS BALANCE IN TAKIGAMI AREA

The gravity changes from relative gravity measurements indicate the mass change in the Takigami geothermal reservoir. Accordingly, we tried estimating the mass balance in Takigami geothermal reservoir.

Figure 8 shows the contour map of gravity changes from 1996 to 1997, just after starting power generation of the Takigami geothermal power plant. The center of 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 transfer associated with the production of the geothermal fluid occurred in the basin structure.

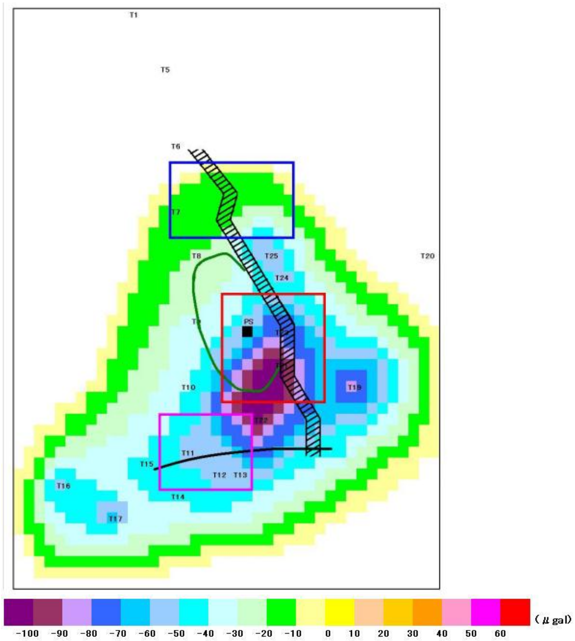

Figure 8: Distribution of gravity changes from 1996 to 1997.

Figure 9 shows the contour map of gravity changes from 1999 to 2002. The residual gravity hardly changes in this entire study area. At some stations on the reinjection zone, the gravity decrease is observed. This indicates reinjected water mostly leaked out of the hydrothermal system, and scarcely remains in the geothermal reservoir.

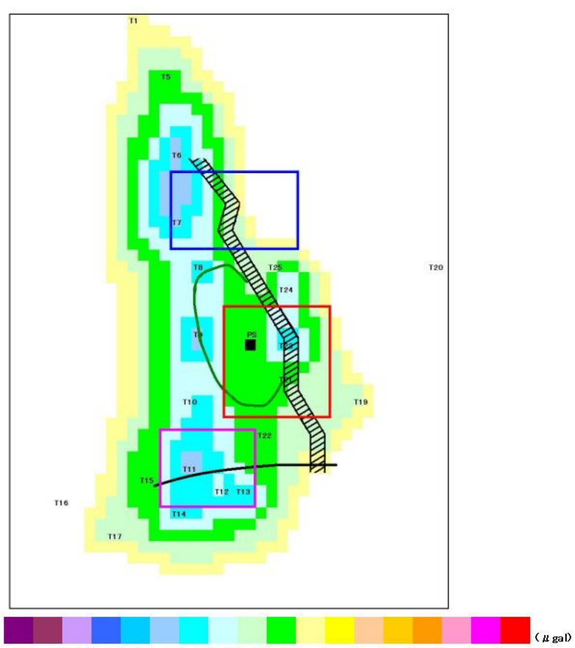

Figure 9: Distribution of gravity changes from 1999 to 2002.

Figure 10 shows the contour map of gravity changes from 2003 to 2007. The gravity changes recovered in this period. Some station is reached to former level. The center of residual gravity increase is located in the southwestern part of the power plant. It seems that the recharge of geothermal fluid has come from southwestern part of the power plant.

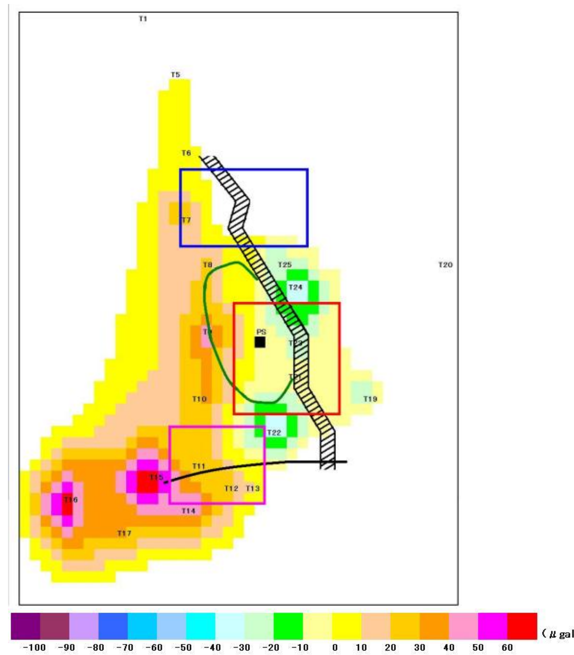

Figure 10: Distribution of gravity changes from 2003 to 2007.

Application of Gauss's Potential Theorem (La Fehr, 1965) to gravity changes gives quantitative estimate of the mass changes. We based on the contour map of the gravity changes (Figure 11, Figure 12 and Figure 13).

Figure 11 shows the mass balance from 1996 to 1997 just after the commencement of the Takigami geothermal power plant. Mass decrease decided 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 2.01 Mt. The difference between the total discharge and the mass decrease is thought to be a natural mass recharge (-6.82Mt) from the surrounding area.

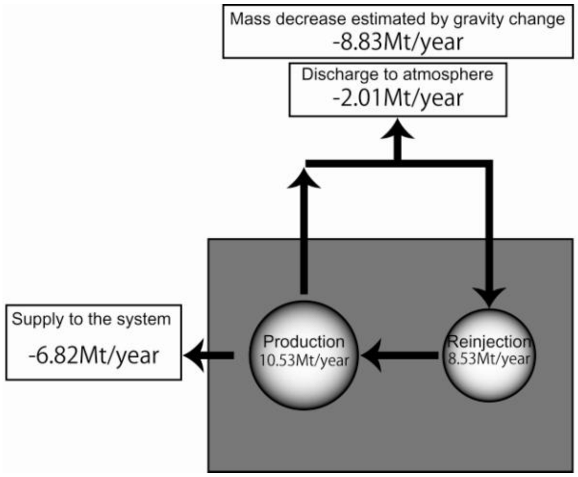

Figure 11: Mass balance based on the contour map of gravity changes at the Takigami geothermal area from 1996 to 1997.

Figure 12 shows the mass balance from 1999 to 2002. In this period, mass decrease decided by gravity change is 1.51 Mt. The total discharge, difference between produced (11.26 Mt) and reinjected (9.68Mt) mass, was 1.58 Mt. The difference between the total discharge and the mass decrease is thought to be a natural mass recharge (0.07Mt) from the surrounding area. This estimate indicates the mass decrease rate has been small because of the recharge from surrounding area caused by pressure decrease in the geothermal reservoir.

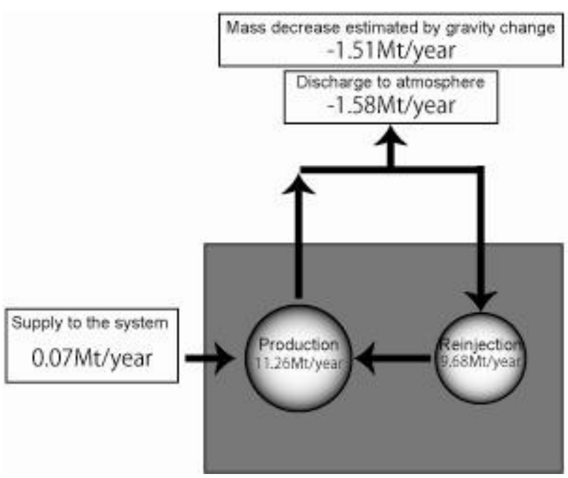

Figure 12: Mass balance based on the contour map of gravity changes at the Takigami geothermal area from 1999 to 2002.

Figure 13 shows the mass balance from 2003 to 2007. In this period, mass increase obtained 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 geothermal fluid flow leached new equilibrium state.

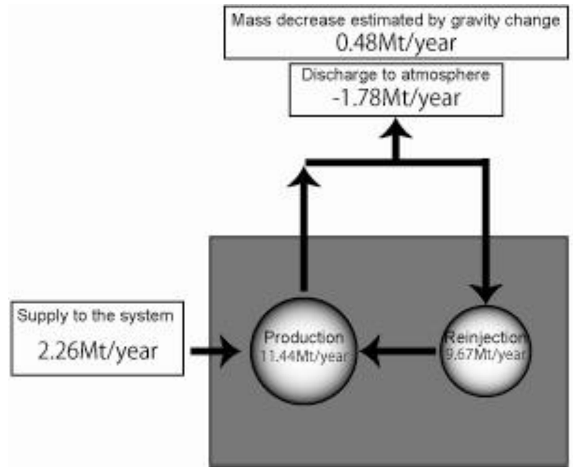

Figure 13: Mass balance based on the contour map of gravity changes at the Takigami geothermal area from 2003 to 2007.

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

CONCEPTUAL MODEL FOR TAKIGAMI HYDROTHERMAL SYSTEM

Based on the results of the gravity changes and the mass balance estimation, we estimated the 4 stages of geothermal fluid flow pattern from temporal gravity change.

1. Before 1996: This stage is natural state. There is fluid flow from South outside of this study area, to E-W faults (Teradoko fault etc.).
2. 1996 – 1998: Second stage is just after commencement of the Takigami geothermal power plant. In the entire study area, drastic decrease happens because of the pressure decrease with production of geothermal fluid.
3. 1998 – 2002: Mass decrease rate changed slowly, though reinjected fluid didn't reach to production zone.
4. Since 2002: Mass increases in the entire study area. Fluid flow has come into the production area from surrounding area.

Based on these classifications, we led a conceptual reservoir model of the Takigami geothermal area (Figure 14).

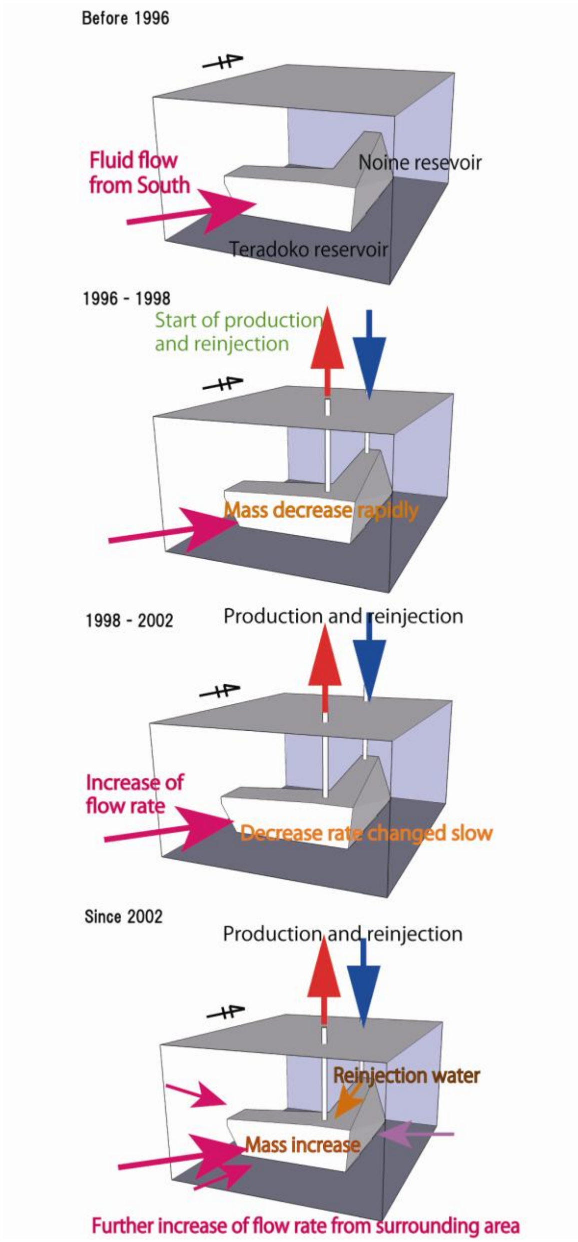

Figure 14: Conceptual model of hydrothermal system alteration

CONCLUSION

We have conducted the repeat relative gravity measurements for about 15 years in the Takigami geothermal area. 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. This study can suggest the hybrid gravity measurement by relative and absolute gravimeters is useful for recognizing the behavior of the geothermal reservoir. Because we judged that the gravity change detected by the relative and absolute gravity measurements illustrated the mass transfer in the geothermal reservoir, we divide the Takigami geothermal area into 3 areas from the pattern of the gravity change after the commencement of the Takigami geothermal power plant, and we estimated the 4 stages of geothermal fluid flow pattern from temporal gravity change. Based on these classifications, we led the conceptual reservoir model of the Takigami geothermal area. We have detected the gravity changes which were consistent with the changes in mass balance in the geothermal reservoir. We estimated that the gravity of the entire observation field in the Takigami geothermal area has recovered as much as the gravity before onset of the power generation.

REFERENCES

Furuya, S., Aoki, M., Gotoh, H. and Takenaka, T. (2000), “Takigami geothermal system, northeastern Kyushu, Japan”, *Geothermics*, **29**, 191-211.

La Fehr, T. R. (1965) “The estimation of the total amount of anomalous mass by Gauss’s Theorem”, *Journal of Geophysical Research*, **70**, 1911-1919.

Takenaka, T., Gotoh, H., Yamamoto, Y. and Furuya, S. (1995), “Exploration and development of the Takigami geothermal system, Kyushu, Japan”, *Journal of the Society of Resource Geology*, **45**, 361-376.