A RESERVOIR MONITORING AND MODELLING USING REPEAT MICROGRAVITY MEASUREMENTS AT OHAAKI GEOTHERMAL FIELD

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ABSTRACT

We continue to repeat microgravity measurements which were begun in 2010 and examine the influence on the reservoir caused by the production and the reinjection at the Ohaaki geothermal field. Repeat microgravity measurements were conducted at Ohaaki geothermal field, New Zealand, in December 2010, February 2012 and September 2012. The measurements were conducted at 26 benchmarks using a SCINTREX CG-3+ gravimeter. After free-air correction and precipitation correction, the maximum gravity increase was +38 µgal at the north side of the eastern production area (BR26) and the maximum gravity decrease was -60 µgal at the northwestern area of the field (H305) from December 2010 to February 2012 (Period 1). The maximum gravity increase was +15 µgal at the northeastern area of the field (A69) and the maximum gravity decrease was -36 µgal at the north side of the western production area (H335) from February 2012 to September 2012 (Period 2). To estimate the mass change in the reservoir, a density change model was created and we calculated the gravity changes from this density change model. We assumed that the absolute density change in the reservoir was 166 kg/m^3, which was caused by phase transition between steam and hot water. The depth of density change was between -200 m asl and -260 m asl. As a result of the calculation, gravity changes were +39 µgal at BR26 and -57 µgal at H305 during Period 1 and +14 µgal at A69 and -35 µgal at H335 during Period 2. These results can represent the results of the gravity measurements.

1. INTRODUCTION

Production and injection in the geothermal field cause underground mass movement. If the production amount is too much, the reservoir drops. It is very important to grasp underground mass movement to prevent the drop of the reservoir and to run a power station stably for a long term. According to Allis and Hunt (1986), underground mass movement could be estimated by the gravity change on the ground at Wairakei geothermal field in New Zealand.

We aimed to continue repeat microgravity measurement which was begun in 2010 and examine the influence on the reservoir caused by the production and the injection at Ohaaki geothermal field.

2. GRAVITY MEASUREMENTS

2.1 Repeat gravity measurements

The dates and period names of repeat microgravity measurements are shown in Table 1. The measurements were made at 26 benchmarks (Fig.1) using a SCINTREX CG-3+ gravity meter. The gravity reference benchmark is H412 because this benchmark is located outside of the resistivity boundary of the Ohaaki geothermal reservoir (Risk, 1993) and its elevation showed a little change during the term from March 2010 to March 2012 (Contact Energy, personal communication).

Table 1: Measurement date and period

Name	First	Second	Third
Date	14 – 17 December 2010	28 February – 2 March 2012	17 – 20 September 2012
Period name	Period 1		
		Period 2	

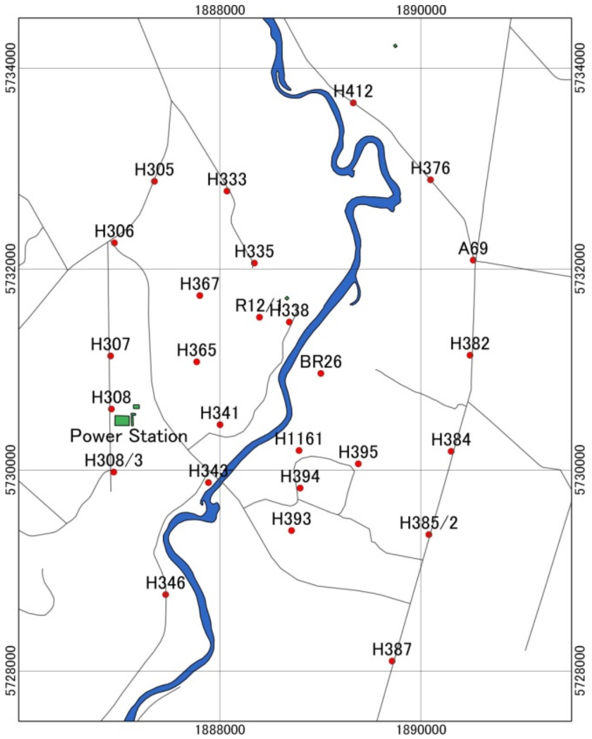

Figure 1: Benchmark location map (New Zealand Transverse Mercator 2000)

2.2 Method of measurement

The benchmarks were divided into several groups and a traversable measurement route, which was linking all benchmarks in a group, was set for each group. All of the measurement routes have the same origination and the two-way measurement method was adopted for the gravity measurement in this study. We set the gravity meter at each benchmark and measured during 2 minutes. A gravity output at a benchmark by the gravity meter is the mean of 120 measurement values during the 2 minutes. After the gravity measurement, we measured the height of the gravity meter from the top of the benchmark, transcribed the various data which were displayed on the LCD to a data sheet, and saved the data in the memory of the gravity meter.

2.3 Data correction

The gravity meter makes tidal correction automatically, but the data were recalculated using GOTIC2 (Matsumoto et al., 2001) which can calculate not only tidal effect, but also ocean loads.

The instrument height correction was made using a value of 0.312 mgal/m for the vertical gravity gradient (Hunt et al., 2002).

3.1 Gravity change

Gravity changes of all benchmarks are shown in Figures 2-6. These plots are the gravity values when we set those of the first measurement (December 2010) as zero, and are the average of the both-way values by the two-way measurement.

Gravity changes were classified in five patterns. Pattern map of classified gravity changes is shown in Figure 7. The gravity values of the third measurement are smaller than those of the first measurement at 19 benchmarks.

3.1.1 Pattern A

15 benchmarks showed gravity decrease during both Period 1 and Period 2 and had a wide distribution, especially were located outside of the geothermal field. Basically decrement during Period 1 was larger than that during Period 2. However decrement during Period 2 was larger than that during Period 1 at H308, H335 and H346, which indicates that the decrease of gravity advances more at these 3 benchmarks.

3.1.2 Pattern B

3 benchmarks showed gravity increase during both Period 1 and Period 2 and were located in the center of the field. The gravity change at H367 and H393 might be influenced by production because they locate near the production wells.

3.1.3 Pattern C

Only the gravity at A69 decreased during Period 1 and increased during Period 2.

3.1.4 Pattern D

The gravity of 3 benchmarks increased during Period 1 and decreased during Period 2, and were located in the production zone.

3.1.5 Pattern E

The gravity changes of 3 benchmarks were less than 10 µgal. Gravity changes which were less than 10 µgal might be caused by measurement error because measurement accuracy was about 10 µgal. Therefore gravity values of these benchmarks were stable.

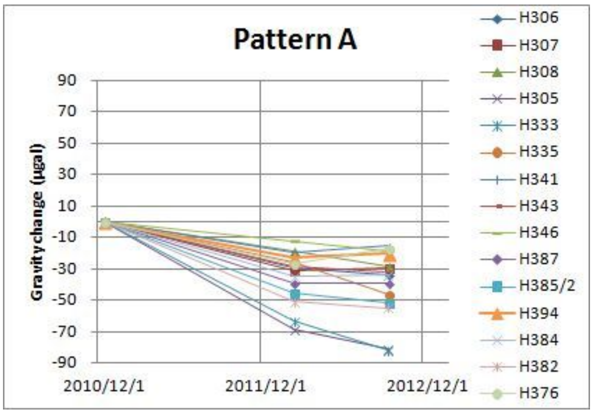

Figure 2: Gravity changes of Pattern A

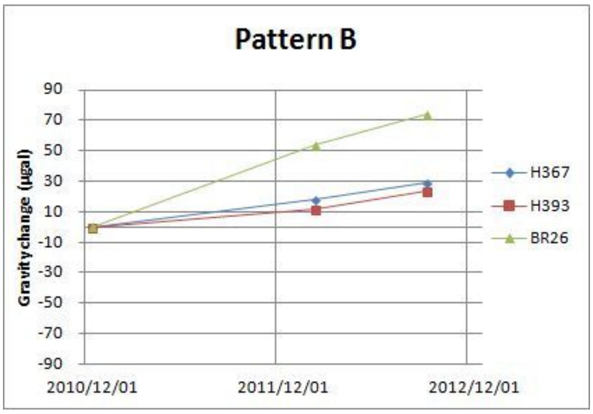

Figure 3: Gravity changes of Pattern B

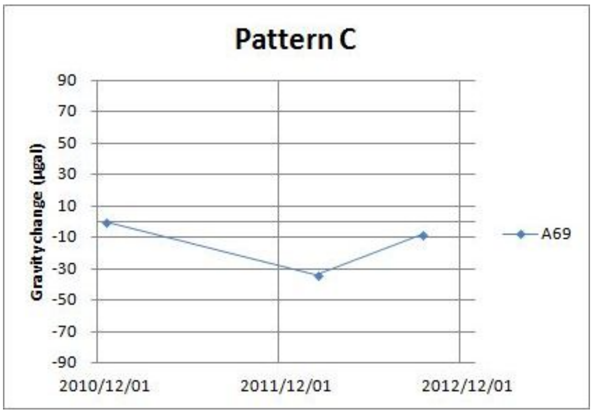

Figure 4: Gravity change of Pattern C

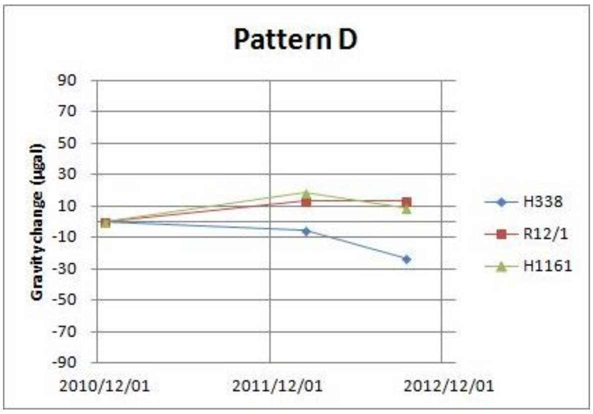

Figure 5: Gravity changes of Pattern D

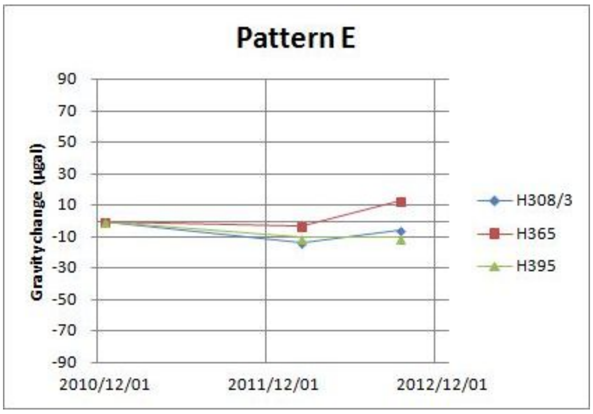

Figure 6: Gravity changes of Pattern E

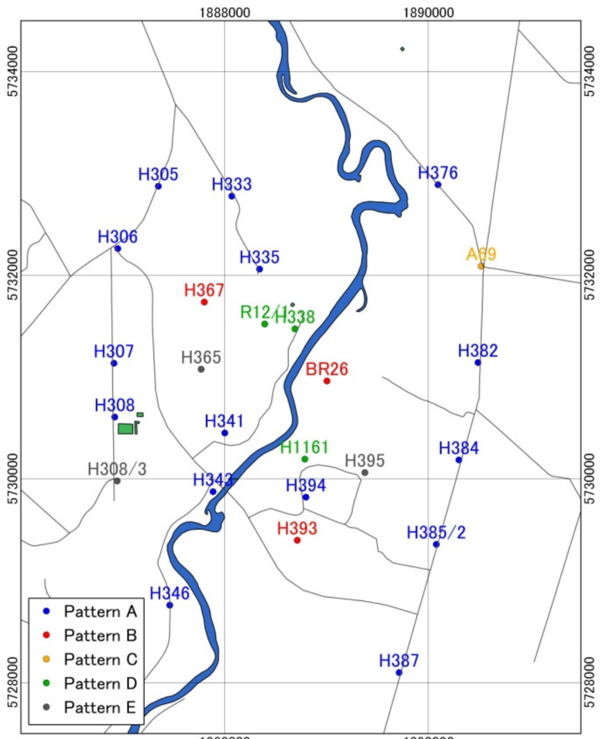

Figure 7: Pattern map

3.2 Spatial gravity changes

Spatial gravity changes for Period 1 and Period 2 are indicated in Figures 8 and 9, respectively.

During Period 1, the gravity values in the northwestern and southeastern parts of this area decreased, contrarily those in the central part increased. Especially, the gravity at BR26 increased +60 μgal during only Period 1.

During Period 2, the gravity changes showed a strong tendency of decrease in the entire area. An exception was the central part, but its gravity increase was smaller than that of Period 1.

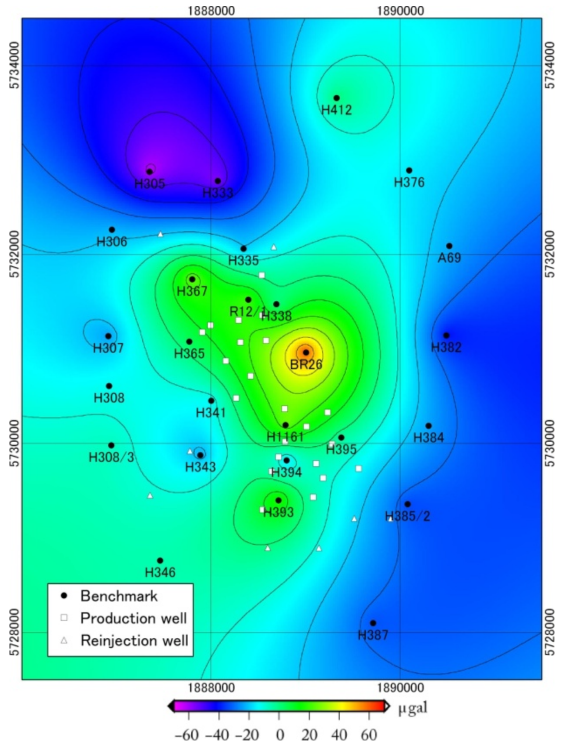

Figure 8: Gravity changes from Dec. 2010 to Feb. 2012

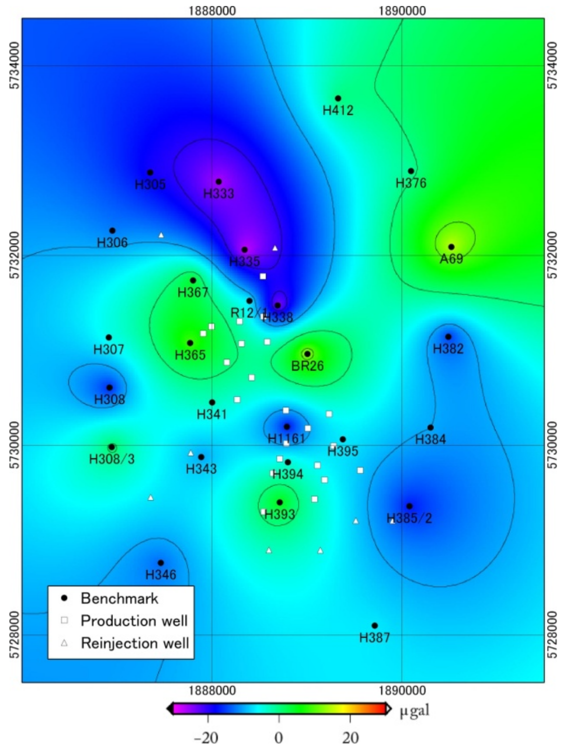

Figure 9: Gravity changes from Feb. 2012 to Sep. 2012

4. INFLUENCE EXCEPT THE DENSITY CHANGE IN THE RESERVOIR

The following 3 factors are considered as causes influencing the gravity.

1) Effects of elevation changes for the benchmarks
2) Effects of rainfall infiltration
3) Effects of production and injection
In this chapter, corrections were made for 1) and 2).

4.1 Effects of elevation changes for the benchmarks

The elevation of the benchmarks changed in Ohaaki. The maximum elevation change was -24 cm from March 2010 to March 2012 (Contact Energy Ltd., personal communication, 2012). Ground subsidence occurred in the entire field. Therefore the free-air correction was made to remove this effect by using the following expression.

$$\Delta F = 0.312\Delta h$$

ΔF : Free-air correction value (mgal)
Δh : Elevation change (m)

Assuming that the rate of elevation change was constant during this period, elevation changes per day were calculated using the leveling data and elevation changes of Period 1 and 2 were calculated.

The gravity changes after the free-air correction of Period 1 and 2 are shown in Figures 10 and 11. As a result of the correction, the areas of the gravity decrease spread wider in the entire area except the eastern part. The maximum correction amount was 45 µgal (Period 1) and 20 µgal (Period 2) at H367.

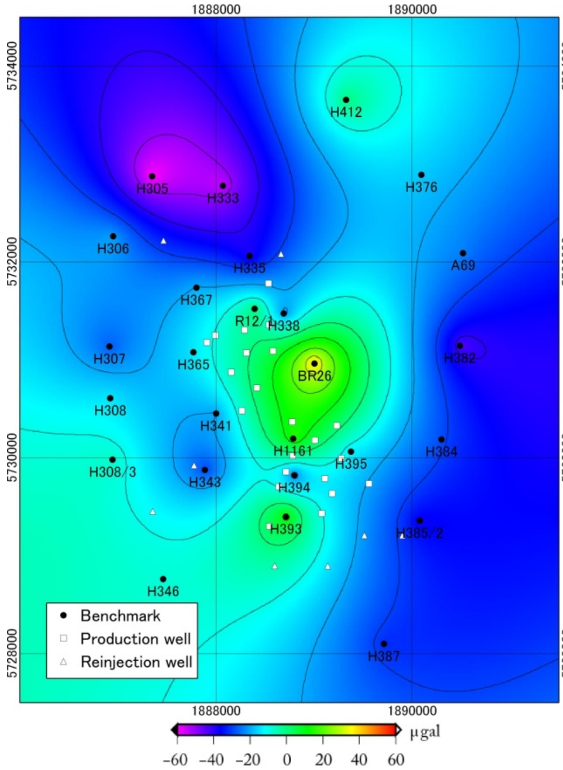

Figure 10: Gravity changes from Dec. 2010 to Feb. 2012 after free-air correction

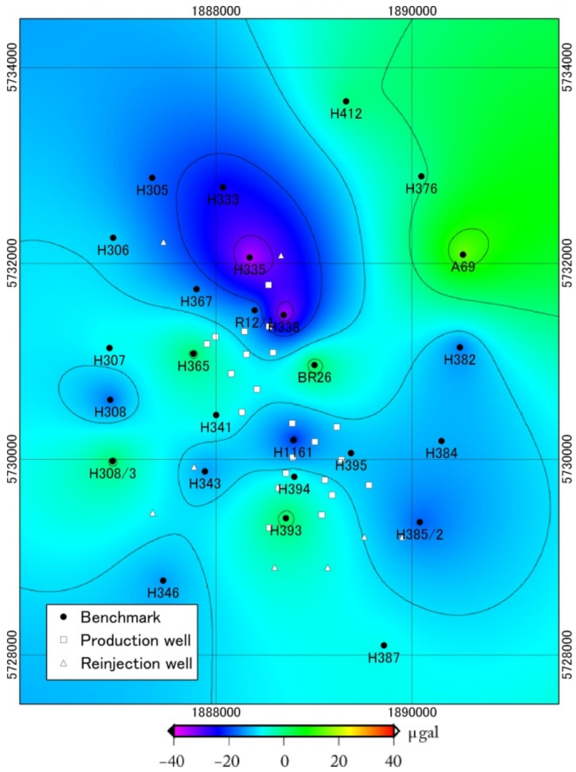

Figure 11: Gravity changes from Feb.2012 to Sep.2012 after free-air correction

4.2 Effects of rainfall infiltration

Precipitation correction was made using the method of Kazama et al. (2011) to remove the effects of rainfall infiltration. The rainfall data were downloaded from the National Institute of Water and Atmospheric Research (NIWA, website).

The result of precipitation correction was +1 µgal at H338, H365, H393, H1161 and BR26 during Period 1 and +1 µgal at H306, H307, H341, H367, H1161 and BR26 during Period 2. As a result, it is thought that the rainfall had little influence on the gravity change in Ohaaki.

5. ESTIMATE OF DENSITY CHANGE IN THE RESERVOIR

Measured gravity changes were caused by water level changes in the reservoir (phase conversion of a steam phase and a hot water phase). The density change in the reservoir was estimated by measured gravity changes.

5.1 Estimated formula of gravity change

The place that a water level change took place was approximated as a cube several tens meters on a side. Density change was given in each block and gravity change was estimated by following formula (Okabe, 1979) and method of Nishijima et al. (2012).

$$g = G\rho\{f(x_2,y_2,z_2) - f(x_2,y_2,z_1) - f(x_2,y_1,z_2) + f(x_2,y_1,z_1) - f(x_1,y_2,z_2) + f(x_1,y_2,z_1) + f(x_1,y_1,z_2) - f(x_1,y_1,z_1)\}$$

where

$$f(x_i, y_j, z_k) = x_i \cdot \ln\left[y_j + (x_i^2 + y_j^2 + z_k^2)^{\frac{1}{2}}\right] + y_j \cdot \ln\left[x_i + (x_i^2 + y_j^2 + z_k^2)^{\frac{1}{2}}\right] + 2z_k \cdot \tan^{-1}\frac{x_i + y_j + (x_i^2 + y_j^2 + z_k^2)^{\frac{1}{2}}}{z_k}$$

$$x_i = x_0 - \xi_i \,, y_j = y_0 - \eta_j \,, z_k = z_0 - \zeta_k$$

g	:	Gravity change
G	:	Gravitational constant
ρ	:	Density
ξ_i, η_j, ζ_k	:	Coordinate of the vertex

5.2 Model area

Gravity changes were estimated in following area. Coordinate system was New Zealand Transverse Mercator 2000. This area was divided into 25m × 25 m blocks. As the depth of the reservoir was estimated to be under 500m (Rissman et al., 2011), the altitude of the upside of the model was -200m. Model area is shown in Figure 12.

EW[m] : 1884500 – 1893000
NS[m] : 5726000 – 5736000

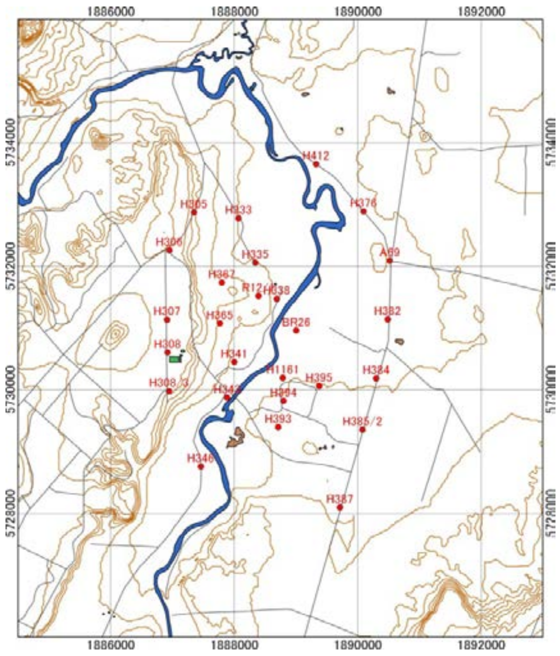

Figure 12: Model area

5.3 Physical properties of the model

Physical property is shown in Table 2. We used 166 kg/m^3 that multiplied porosity by the density difference as a density change.

Table 2 Physical properties

Temperature [˚C]	220 (Christenson et al., 2002)
Density difference [kg/m^3]	828 Water density : 840 Steam density : 12
Porosity [-]	0.2 (Hunt and Papasin., Personal communication, 2007)

5.4 Distribution of density change

It is assumed that the gravity changes were caused by the water level change in the upper reservoir and the water level change is caused by phase conversion between a steam phase and a hot water phase. Therefore density change blocks were given in the place deeper than -200 m asl. The location of density change is shown in Figures 13 and 14. Density change blocks were given along the faults from -200m asl to -260m asl. The distribution of density change blocks indicate the possibility that density change fluid moves along the faults.

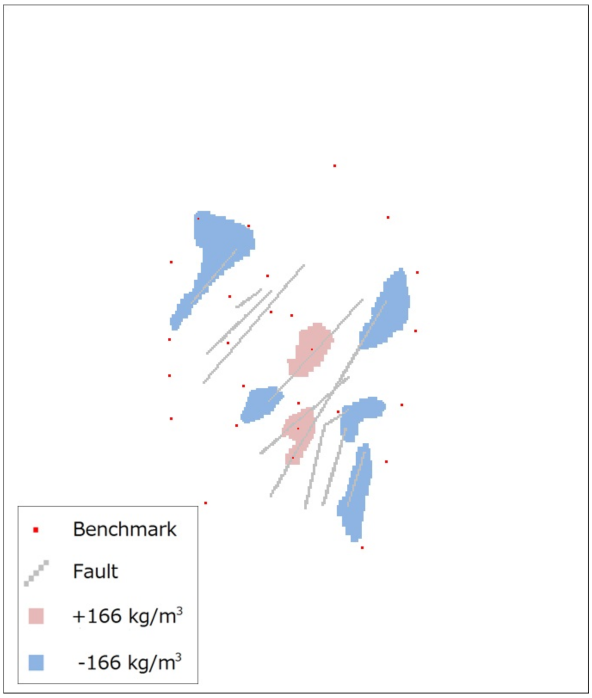

Figure 13: Distribution map of density change (Period 1)

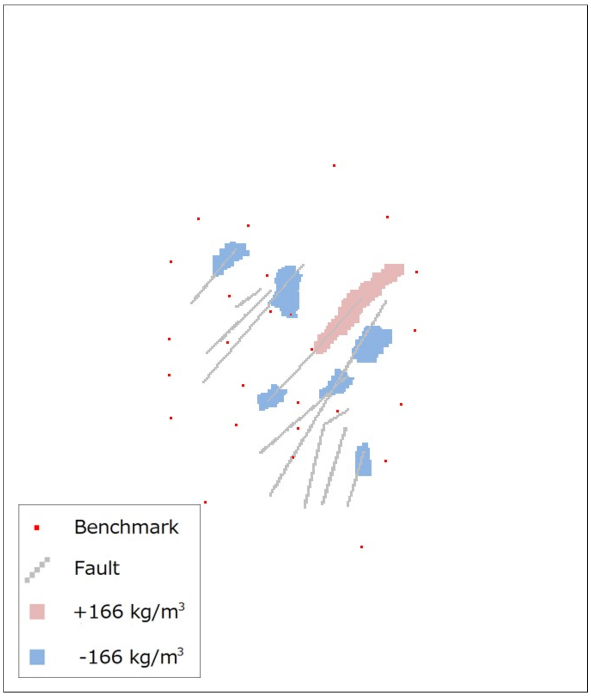

Figure 14: Distribution map of density change (Period 2)

5.5 Result

5.5.1 Period 1

The model result is shown in Figure 15. In this model, the gravity change was +39µgal at BR26 and -57µgal at H305. This result could reproduce measured gravity change (+38µgal at BR26 and -60µgal at H305). However, at H338 the result was +8µgal in spite of the fact that measured gravity change was -20µgal and at H394 the result was +23µgal in spite of the fact that measured gravity change was -22µgal. The common point of these 2 benchmarks was that both benchmarks locate between the areas of gravity increase. It is thought that such gravity change was caused by a density change in more shallow part or a problem of measurement.

It is thought that a steam phase converted to a hot water phase in the density increased area and a hot water phase converted to a steam phase in the density decreased area.

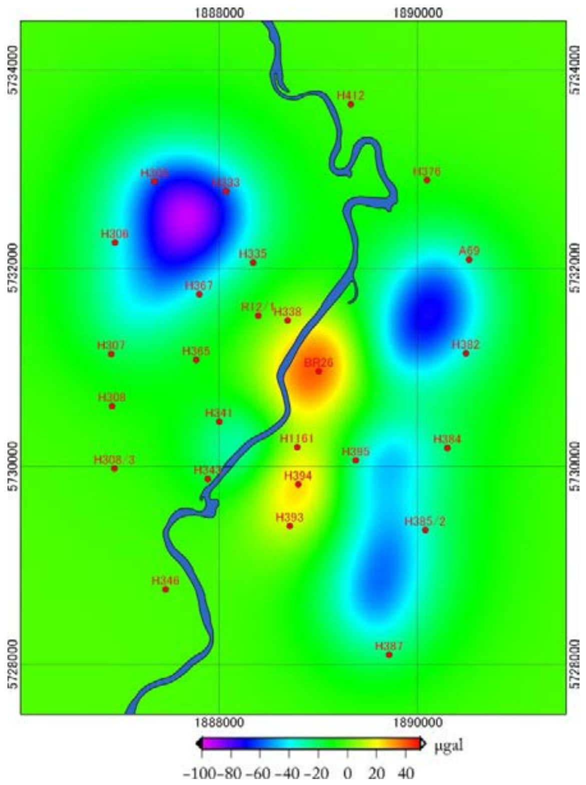

Figure 15: Gravity change model from Dec.2010 to Feb.2012

5.5.2 Period 2

The model result is shown in Figure 16. In this model, the gravity change was +14µgal at A69 and -35µgal at H335. This result could reproduce measured gravity change (+15µgal at A69 and -36µgal at H335). However, at H308 and H346, the result was 14µgal larger than measured gravity change. It is thought that a density change was caused near H308 and H346 where there are not faults.

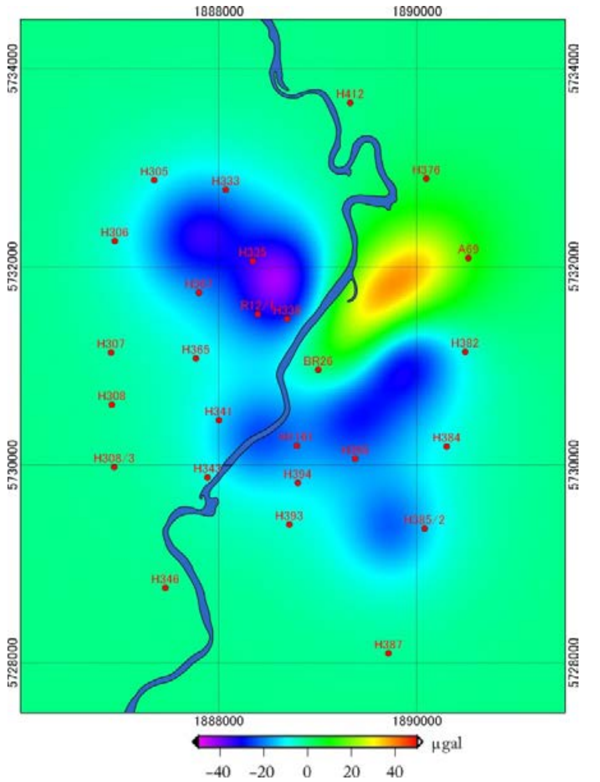

Figure 16: Gravity change model from Feb.2012 to Sep.2012

6. CONCLUSIONS

1. We have conducted the microgravity measurements in December 2010, February 2012 and September 2012. It is thought that the density change in the reservoir can be monitored by continuing repeat microgravity measurements in the Ohaaki geothermal field.

2. The gravity changes had 5 patterns.

3. The gravity values in the northwestern and southeastern parts of the Ohaaki geothermal field decreased in Periods 1 and 2.

4. After the elevation change correction, the areas of the gravity decrease spread wider in the entire area except the eastern part.

5. It is thought that gravity change was caused by the density change in the reservoir because gravity change was estimated by the density change model.

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REFERENCES

Allis, R.G. and Hunt, T.M. : Analysis of exploitation-induced gravity changes at Wairakei Geothermal Field, Geophysics, 51,8. pp. 1647-1660. (1986).

Christenson, B.W., Mroczek, E.K., Kennedy, B.M., Soest, M.C., Stewart, M.K. and Lyon, G. : Ohaaki reservoir chemistry : characteristics of an arc-type hydrothermal system in the Taupo Volcanic Zone, New Zealand, Journal of Volcanology and Geothermal Research, 115. pp. 53-82. (2002).

Hunt, T.M., Sugihara, M., Sato, T. and Takehara, T. : Measurement and use of the vertical gravity gradient in correcting repeat microgravity measurements for the effects of ground subsidence in geothermal systems, Geothermics, 31. pp. 525-543. (2002).

Kazama, T., Yamamoto, K. and Fukuda, Y. : Hydrological disturbance corrections for relative gravity data observed at Sakurajima Volcano, 116th Meeting of the Geodetic Society of Japan. p. 17. (2011).

Matsumoto, K, Sato, T., Takanezawa, T. and Ooe, M. : GOTIC2:A Program for Computation of Oceanic Tidal Loading Effect, Journal of the Geodetic Society of Japan, 47,1. pp. 243-248. (2001).

National Institute of Water and Atmospheric Research (website) Welcome to the Climate Database, http://cliflo.niwa.co.nz/, accessed January 23, 2013.

Nishijima, J., Fujimitsu, Y., Oka, D., Takayama, J. and Hiraga, N. : Hybrid Micro-gravity Measurement at Ogiri Geothermal Power Plant – Gravity Correction Caused by Shallow Groundwater Level Change -, 2012 Annual Meeting Geothermal Research Society of Japan Abstracts with Programs. p. B30. (2012).

Okabe, M. : Analytical Expressions for Gravity Anomalies Due to Homogeneous Polyhedral Bodies and Translations into Magnetic Anomalies, Geophysics, 44,4. pp. 730-741. (1979).

Risk, G.F.: Resurvey of resistivity boundary of Ohaaki Geothermal Field, 1975-1993, Proceedings of the 15th NZ Geothermal Workshop. pp. 195-200. (1993).

Rissmann, C., Nicol, A., Cole, J., Kennedy, B., Fairley, J., Christenson, B., Leybourne, M., Milicich, S., Ring, U. and Gravley, D.: Fluid flow associated with silicic lava domes and faults, Ohaaki hydrothermal field, New Zealand., Journal of Volcanology and Geothermal Research 204. pp. 12-26. (2011).

Rosenberg, M.D., Bignall, G., Bromley C.J. and Kilgour, G.N. :Well Siting Options for Production and Injection Development of Ohaaki Geothermal Field., GNS Science Consultancy Report 2007, 46. pp. 1-13. (2007).