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RESERVOIR MONITORING BY OBSERVATION OF GRAVITY CHANGES AT SOME GEOTHERMAL FIELDS IN KYUSHU, JAPAN

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ABSTRACT

Repeat gravity measurements have been conducted at four geothermal fields (Takigami, Oguni, Hatchobaru and Yamakawa) in Kyushu, Japan to monitor movement of geothermal fluid. For example, gravity changes at 26 stations have been monitored since May 1991 to study reservoir behavior in Takigami geothermal field. At some fields, the observed gravity changes include the effect of shallow ground water level change. These are removed using the relationship between gravity and precipitation derived from multivariate regression analysis, and precipitation data collected prior to the gravity measurements.

An application of Gauss's Potential Theorem to gravity changes in Hatchobaru geothermal field show that most of the mass discharged to the atmosphere has been replaced by natural inflow. These estimation and the results of repeat gravity measurements show that repeat gravity measurements is an effective method to monitor the underground hydrological systems.

1. INTRODUCTION

The production and reinjection of geothermal fluid cause mass fluid movement and mass redistributions, which can cause measurable gravity changes at the ground surface. Repeat gravity measurements have been carried out in some geothermal fields. Gravity decreases of up to 1000μgal have been measured after 30 years of production from the Wairakei geothermal field, New Zealand (Allis and Hunt, 1986).

A strong qualitative correlation has been observed between the pressure change and gravity change at the Hatchobaru geothermal field, Oita, Japan (Tagomori et. al, 1996), but quantitative correlation are poor. The observed gravity changes depend significantly on changes in shallow groundwater level change (Ehara et. al, 1995). It is necessary to eliminate such effects before applying repeat gravity measurements for the geothermal reservoir monitoring.

2. REPEAT GRAVITY MEASUREMENTS

We have been regularly making repeat gravity measurements at four geothermal fields: Takigami, Hatchobaru, Oguni (central Kyushu) and Yamagawa (southern Kyushu). We used Scintrex CG-3 and CG-3M gravimeters to measure precise gravity change. At each geothermal field, repeat gravity measurements were made at intervals of a few weeks to several months. The two-way measurement method was used to evaluate the instrumental drift and precision; we estimated the errors of observation as ±10 μgal at each study fields.

3. GRAVITY CHANGES

3.1 Takigami geothermal field

Takigami geothermal field is located in the southwestern part of Oita Prefecture, central Kyushu, Japan (Fig.1). The Takigami power station (25MW) was completed in November 1996. We started repeat gravity measurements in May 1991, at 26 observation stations. The geothermal reservoir is a fractured type. The deep geothermal fluid rises along the some faults in the southwestern part and flows laterally towards the northeastern part of the field. Therefore the production zone is in the southwestern part and the reinjection zone is in the northeastern part of the field. The production depth is about 2500m and the reinjection depth from 1000m to 1500m.

We determined the gravity changes caused by seasonal changes of the shallow groundwater level using a multivariate regression model (Nishijima et. al, 1999) (Fig.2). This enabled us to eliminate the effects of shallow groundwater level changes and so extract the gravity changes associated with the production and reinjection of geothermal fluid.
The residual gravity (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. The data suggest there were decreases of residual gravity (up to 40 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 (Fig. 3). Fig. 3 shows that the center of residual gravity change is located just to the east of the Takigami geothermal power station. The center of this change is located into the basin structure (Hayashi et. al, 1988). The mass movement associated with the production of the geothermal fluid occurred in basin structure.

3.2 Hatchobaru geothermal field

Hatchobaru geothermal field is located 5km northwest of Kuju volcano, central Kyushu, and it shows a fractured type of geothermal reservoir. At this site, Hatchobaru No. 1 unit (55MW) was completed in June 1977, and Hatchobaru No. 2 unit (55MW) was completed June 1990. We started repeat gravity measurements in May 1990 just before the commencement of operation of the No. 2 unit. There are 44 observation stations for repeat gravity measurements. The production zone is in the southeastern part and the reinjection zone is in the northwestern part of the field. The depth of main production points are from 1000m to 2500m and that of main reinjection points are 1000m to 1500m. The deep geothermal fluid rises along some fractures in the southeastern part of the field and flows towards the northwest laterally.

Increases in gravity were observed in the reinjection zone and part of the production zone just after the commencement of No. 2 unit. After that, a rapid decrease of gravity (up to 200 μgal) was observed in production area (Fig. 4).

A contour map of gravity change (from June 1990 to November 1992) (Fig. 5) shows there is the zone of gravity decrease around the production zone, especially towards to southern part of production zone.

Leveling surveys showed that vertical ground movements ranged from –15mm to +35mm from August 1990 to March 1996. Assuming a free-air gradient of -308.6μgal/m, this ground movement caused about –10 to +5μgal of gravity change (Tagomori et al., 1996). The effect of vertical ground movement on observed gravity is therefore negligible.

The pattern of gravity change in the production zone is very similar to that of reservoir pressure, and there is good correlation (>0.8) between gravity change and reservoir pressure (Tagomori et al., 1996). This result shows that the decrease of gravity in the production zone reflects the net mass loss in the reservoir.

Application of Gauss's Potential Theorem (La Fehr, 1965) to gravity changes gives quantitative estimate of the mass changes. Based on the produced and reinjected mass and the values of the net mass change, we calculate there has been a natural mass recharge of 16.3Mt (Fig. 6).

3.3 Oguni geothermal field

Oguni geothermal field is located in the northeast part of Kumamoto Prefecture. We started repeat gravity measurements in September 1993, at 28 observation stations. In this field, we try to grasp the background gravity changes before development to estimate the background gravity change by applying a statistical technique.

Gravity changes (up to 170μgal) were observed from September 1993 to August 1997. The contour maps of gravity change extend from the top of Mt. Waita to the northwest foot of it (Fig. 7). Examination of the data shows there is a good correlation of gravity with precipitation, with a phase lag of about 6 months. As a result, these gravity changes are attributed to changes of shallow ground water level.

3.4 Yamagawa geothermal field

Yamagawa geothermal field is located southern Kyushu. The Yamagawa power station (30MW) was completed in March 1995.We started repeat gravity measurements in June 1996, at 22 observation stations, and we have repeated gravity measurements at an interval of about three months. The production zone is in the eastern part and the reinjection zone is in the western part of the field. The depth of main production points are from 1500m to 2500m and that of main reinjection points are about 1200m.

These gravity changes can be subdivided into two types of response (Fig. 8). On one hand, the gravity changes seasonally, and there is good correlation between the gravity changes and shallow ground water level changes. This type is located in the southern part of the field and is attributed to changes of the shallow ground water level change.

On the other hand, the stations that are located in the northern part of the field, show increases in gravity from June 1996 to August 1997 and decreases from August 1997 to December 1997. There is poor correlation between gravity changes and ground water level changes.

4. DISCUSSIONS

The above results have some common features:

4. 1 Vertical ground movement

Leveling surveys show there are vertical ground movements in each geothermal field, but they are less than 1cm/year. Assuming a normal free-air gradient of -308.6μgal/m, ground movement causes gravity changes less than 3μgal. These changes are much smaller than the observed gravity changes. Consequently, the gravity effects of vertical ground movements are negligible at least in the short term (several years), but may be significant in the long-term (more than 10 years). If the observation period becomes long, then it will be necessary to correct for this effect.

4.2 Gravity changes caused by shallow ground water level change

We observed gravity changes (up to 150μgal) at Takigami and Oguni geothermal fields before exploitation. In these fields there appears to be a relationship between gravity change and ground water level change. Fig. 9 shows the changes of gravity and groundwater level at Takigami geothermal field. Although long-term trends are clearly correlated, the high-frequency content obviously differs. Although these wells distance is about 1km, the groundwater levels are significantly different in phase and amplitude, indicating the groundwater level changes are controlled by local hydrological structure. Therefore, we examined the relationship between gravity and precipitation, which is believed to control the groundwater level change of this area. This shows there is a good correlation (>0.7) for a phase lag of about 3 months (Fig. 10).

The observed gravity changes in these fields clearly depend significantly on changes in shallow groundwater level change.

4.3 Common feature of contour maps of gravity changes

The pattern of gravity change reflects underground structure and appears to be related to the strike of faults in each geothermal field (Fig. 5). Also, there is a good correlation between gravity changes and altitude (Fig. 11). Generally, at higher altitudes, the ground water level changes are greater. These above show that the flow of water is controlled to the faults and observed gravity changes catch the flow of the water that was controlled to the faults.

5. CONCLUSIONS

- Repeat gravity measurements have been made at four geothermal fields in Kyushu, since 1990.

- In some fields, the gravity effects of seasonal changes in groundwater level mask the effects of reservoir changes. However, multivariate regression modeling of the gravity and precipitation data has enabled the effects of groundwater level changes to be determined, with an accuracy of ±10μgal, and removed to isolate the changes associated with production and reinjection.

- In all four fields, the gravity effects of ground subsidence are negligible.

- In Hatchobaru geothermal field, there is appears to be a good correlation between reservoir pressure changes and gravity changes.

- The studies suggest that repeat gravity measurements are an effective method to monitor geothermal systems.

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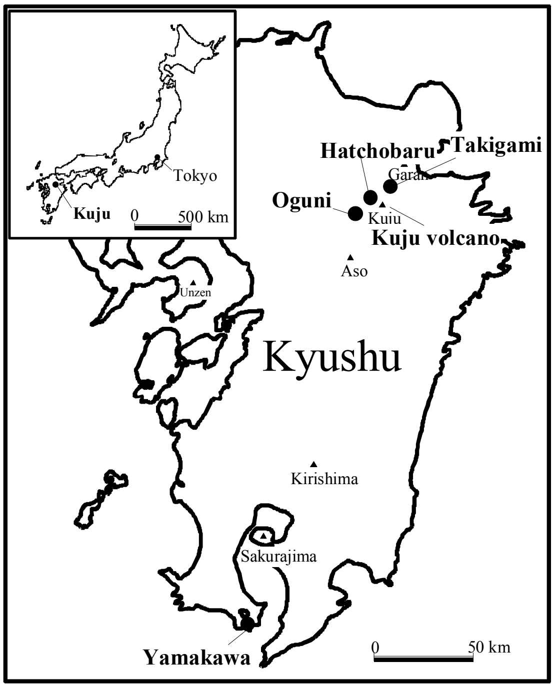

Figure 1. Location of fields in which repeat gravity measurements have been made.

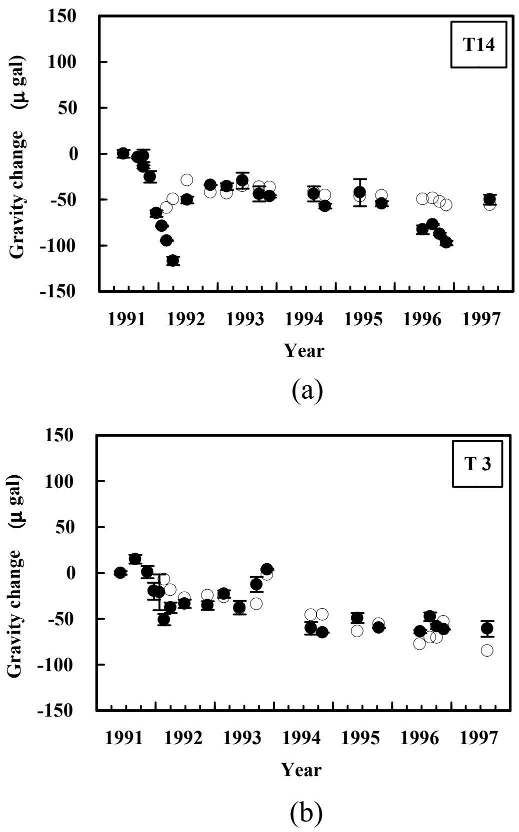

Figure 2. Comparison between the observed and determined gravity changes at Takigami geothermal field. (a): in the production zone, (b):in the reinjection zone.

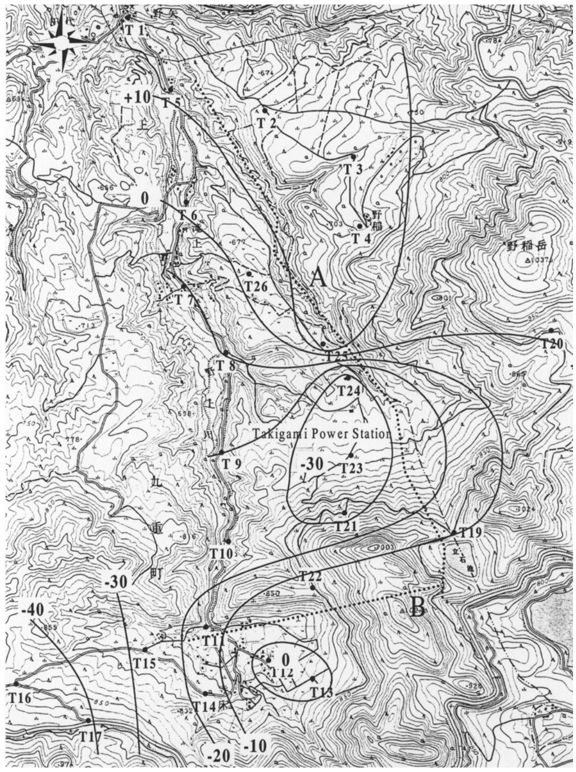

Figure 3. Contour map of the gravity changes (effects of precipitation removed), at Takigami geothermal field from October 1995 to June 1996.

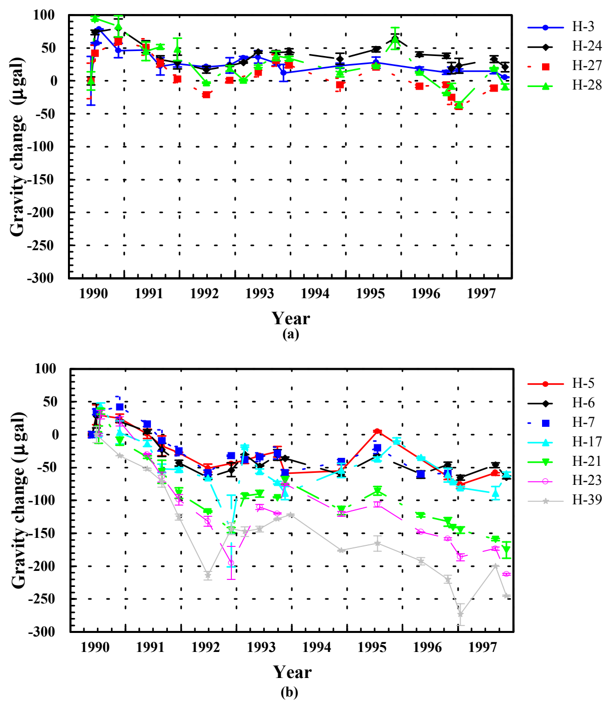

Figure 4. Examples of gravity change at Hatchobaru geothermal field. (a): in the reinjection zone, (b):in the production zone.

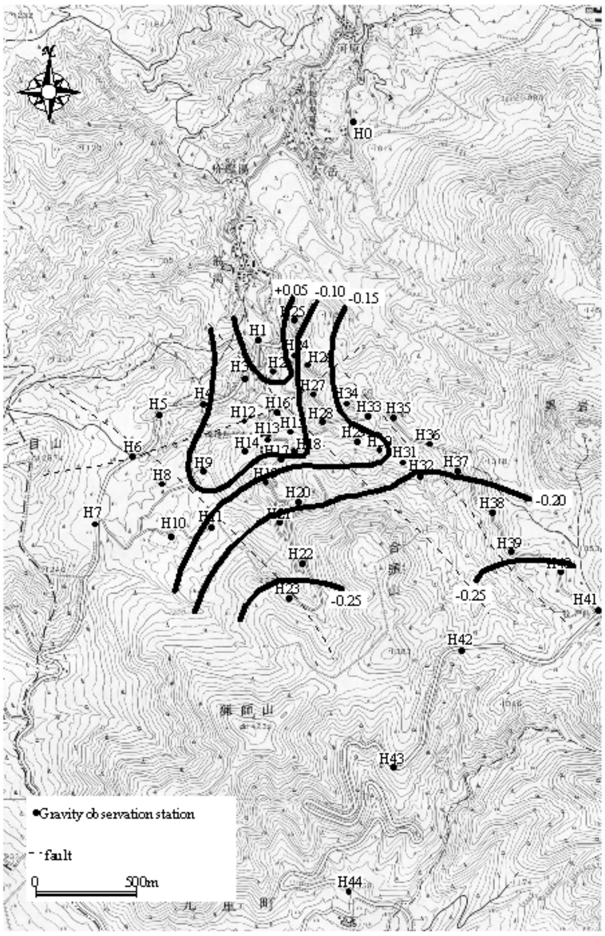

Figure 5. Contour map of the gravity changes at Hatchobaru geothermal Field from June 1990 to November 1992.

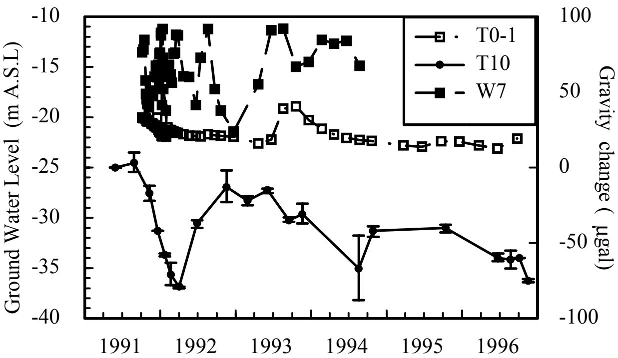

Figure 9. Changes of the ground water level in Well T0-1 and Well W7, and gravity changes (T10) at Takigami geothermal field.

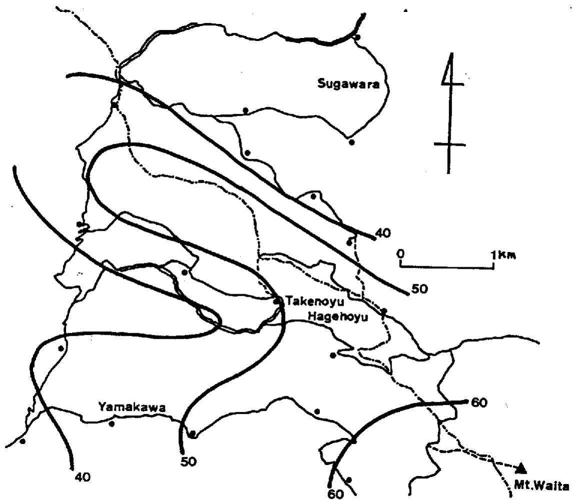

Figure 7. Contour map of the gravity changes at Oguni geothermal Field from November 1993 to January 1994.

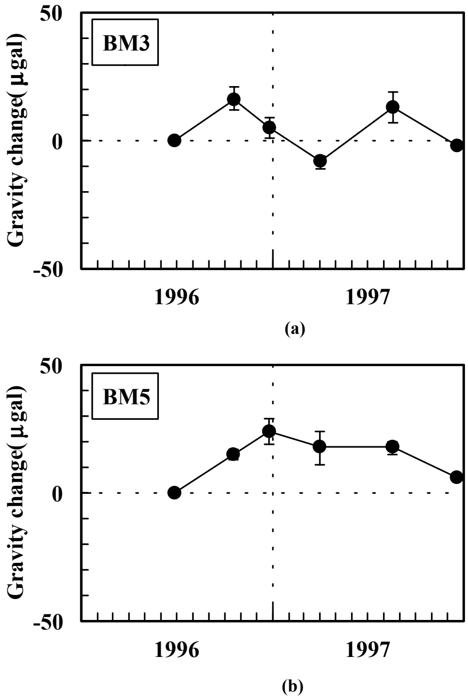

Figure 8. Examples of gravity change at Yamagawa geothermal field. (a): in the southern part of the field, (b):in the northern part of the field.

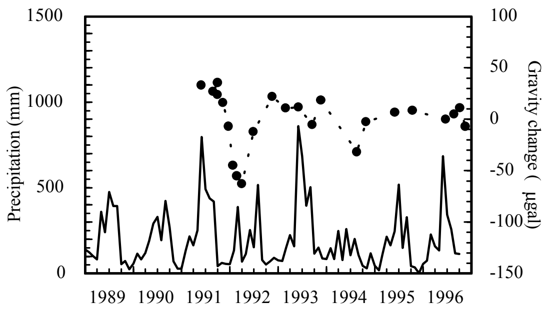

Figure 10. Comparison between precipitation and gravity. Long-term trend subtracted from gravity at Takigami geothermal field.

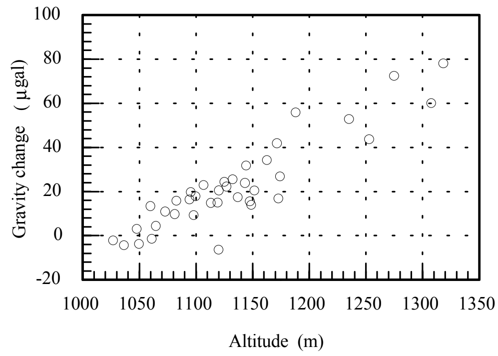

Figure 11. Comparison between gravity change and altitude.

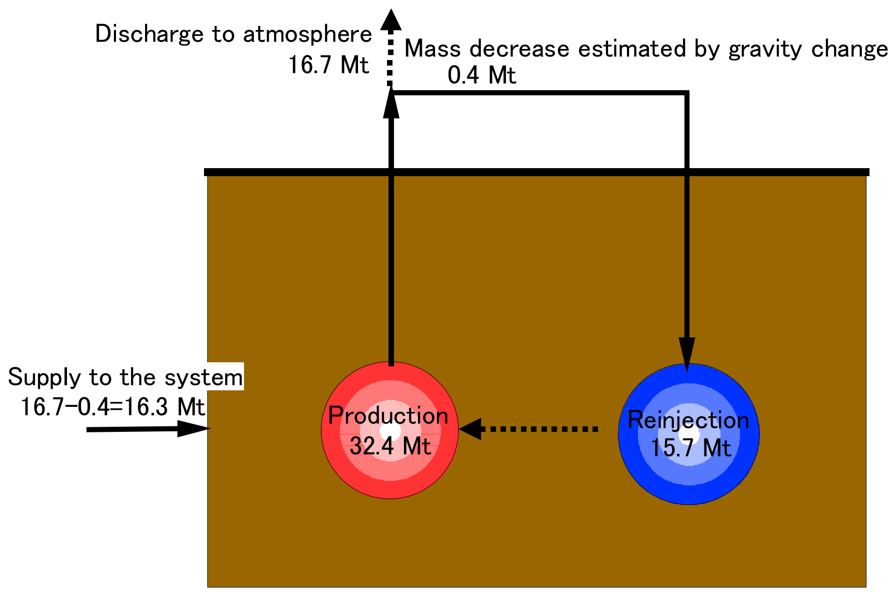

Figure 6. Mass balance in the production and reinjection zones at Hatchobaru geothermal field, from August 1991 to May 1993.