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RESERVOIR MONITORING BY REPEAT GRAVITY MEASUREMENTS AT THE TAKIGAMI GEOTHERMAL FIELD, CENTRAL KYUSHU, JAPAN

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ABSTRACT

Repeat gravity measurements have been conducted since May 1991 at the Takigami geothermal field in Kyushu, Japan in order to monitor the underground geothermal fluid flow system. The observed gravity changes include gravity changes due to shallow groundwater level change. Therefore, we tried to remove the influence of shallow groundwater by applying a statistical technique in order to isolate the gravity change due to the mass change associated with the commencement of the production and reinjection of geothermal fluids at the Takigami geothermal power station in 1996. Although an obvious correlation between measured shallow groundwater level change and gravity change wasn't found out, the multivariate regression analysis was applied in order to establish the relationship between gravity and precipitation, and a good correlation was obtained. Therefore, it is now possible to estimate the gravity change due to groundwater level change at each observation station by using the precipitation data collected prior to the gravity measurements. We thereby define the residual gravity, which is the observed gravity minus this estimated gravity. The results of repeat gravity measurements show that repeat gravity surveys is an effective method to monitor the underground hydrological systems.

1. INTRODUCTION

In a geothermal field, production and reinjection of geothermal fluid cause mass movement. These mass redistributions can cause measurable gravity changes at the ground surface. Repeat gravity measurements have been carried out in some geothermal fields. Gravity decreased by up to 1000 microgals during 30 years of production in the Wairakei geothermal field, New Zealand (Allis and Hunt, 1986).

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

We have been conducting the repeat gravity measurements in several geothermal fields in Kyushu. The places are Hatchobaru, Takigami, Oguni and Yamagawa in which geothermal power plants are in operation or under construction (Fig. 1). Especially, repeat gravity measurements at the Takigami geothermal field were started before the geothermal exploitation. We tried to determine the gravity changes caused by seasonal changes of shallow groundwater level using statistical methods. We applied multivariate regression analysis in order to eliminate the effect of shallow groundwater level change and to determine the gravity change associated with the production and reinjection of geothermal fluid.

2. REPEAT GRAVITY MEASUREMENTS IN TAKIGAMI FIELD

The Takigami geothermal field is located in a hill country (about 700–800 m asl) of the southwestern part of Oita prefecture, central Kyushu, Japan (Fig. 1, Fig. 2). This field is characterized by absence of geothermal features such as fumaroles and steaming grounds. Only a few small hot springs exist 3-4 km north from The Takigami power station (25 MW). Many kinds of explorations for the geothermal exploitation had been conducted from 1979 to 1989, and Hayashi et al. (1988) divided this field vertically into three parts from the geological and thermal viewpoints (Fig. 3). The upper layer is composed by the Noine-dake Volcanic Rocks and the Ajibaru Formation of Quaternary. This layer shows low thermal gradient and low temperature below 50 ^{o}C. The middle layer is composed by Quaternary dacitic and andesitic volcanics called the Takigami Formation in which the thermal gradient is high. The lower layer is Tertiary andesitic rocks called the Usa Group, isothermal gradient and high temperature (160-260 ^{o}C). This layer is the geothermal reservoir of this field. After the explorations, the production and reinjection test was conducted from November 1991 to February 1992. During the test, the amounts of produced and reinjected fluids were about 3 Mt and 2 Mt, and we detected the gravity change associated with this reinjection (Ehara et al., 1995). Construction of the power station began in 1995. After the commencement of the production and reinjection in May 1996, The Takigami power station was completed in November 1996.

The 26 observation stations for the repeat gravity measurements are shown in Fig. 2. The production zone is in the southern part, and the reinjection zone is in the northern part of this field. The total production rate is about 1270 t/h (steam 240 t/h, hot water 1030 t/h), and reinjection rate is about 1030 t/h. Leveling survey data from 1982 shows that the ground subsidence (< 2 cm) had occurred in a part of the production zone during October 1992 and March 1998, however it stopped thereafter. We used two gravimeters, Scintrex CG-3 and CG-3M, to measure precise gravity change around the power station. The repeat gravity measurements were conducted from May 1991 to July 1998 at 1-3 month intervals. The two-way measurement method was taken to evaluate instrument drift and measurement precision. We set station T1 as the gravity reference station, and confirmed its stability of gravity value by comparing with the value of a first-order bench mark (No.2562) about 2 km NE from T1. We estimate the errors in the gravity observations to be less than 10 microgals, so the effect of ground subsidence (< about 6 microgals by the normal free-air gradient) is thought to be negligible.

3. MULTIVARIATE REGRESSION MODEL

To detect changes in deep geothermal fluid flow from repeat gravity measurements, it is necessary to estimate the effect of shallow groundwater changes.
By extending the theory of the autoregressive model (Koike et al., 1991), a multivariate regression model was constructed

$$y_t = \sum_{i=0}^{m} \beta_i x_{t-1} + \varepsilon_i \qquad (1)$$

relating the changes of shallow groundwater level to the observed gravity changes:
where y_t is a criterion variate, x_t is an explanatory variate with β_i the coefficient of regression, m is an optimum degree of fit, ε_i is white noise.
At first, we intended to construct a multivariate regression model relating change of observed groundwater level with gravity. Fig. 4 shows the changes of gravity (at station T10) and groundwater level (in wells TO-1, W-7). Although long-term trends are clearly correlated, the high-frequency content obviously differs. Moreover, the groundwater levels of these two observation wells are significantly different in phase and amplitude, suggesting that the groundwater level change is controlled by local hydrological structure, or suggesting that the level of TO-1 is for a confined aquifer and W-7 for an unconfined aquifer. For this reason, we tried to correlate gravity with precipitation, which is believed to control the groundwater level change of this area. Annual precipitation at Takigami is about 2600 mm and the rainfall is seasonal. A comparison between precipitation and gravity (Fig. 5) shows that there is a phase lag of about 3 months. However, there is good correlation (> 0.7) when we shift the phase contrast and calculate the coefficient of correlation. Therefore, we quantitatively estimated the effect of background gravity changes associated with groundwater level changes using a precipitation-gravity correlation.
Two examples of comparison between the observed and estimated gravity in the production and reinjection zones are shown in Fig. 6. As a result, the optimum degrees were estimated 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 accuracy of the background gravity is estimated to be ±10 microgals. Before exploitation, there was good agreement between the observed and estimated gravity. However, there are differences up to 40 microgals 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.

4. DISCUSSION

The residual gravity (due to reservoir effects), taken as the difference between observed and estimated gravity at each observation station, can be divided into four types of response during the period from October 1995 to August 1997 (Fig. 7).

Type A
This type of gravity change response is seen around the reinjection zone located in northern part of observation area. Just after the commencement of reinjection of geothermal fluid, gravity increased, and it decreased from August to November 1996. After that, residual gravity values increased once again during November 1996 and August 1997.

Type B
As soon as the production and reinjection of the geothermal fluid began, a slight decrease of the residual gravity values occurred, but afterwards, there were no significant residual gravity changes.

Type C
This type of response is seen at observation stations located in the production zone along the Teradoko Fault, in the southern part of the observation area. Gravity decreased from the start of production until November 1996, stabilized afterward, then started increasing.

Type D
This type of response is typical of stations located in the production zone along the Noine Fault, in the eastern part of the observation area. A decrease of residual gravity occurred immediately after geothermal fluid production started, and between June and August 1996 gravity increased sharply. After that, residual gravity values gradually decreased.

In summary, a decrease of the residual gravity was seen in the production zone and an increase in the reinjection zone just after the production and reinjection of the geothermal fluid started.
Two contour maps of residual gravity change are shown in Fig. 8(a) and (b). The gravity change from October 1995 to June 1996 (Fig. 8(a)) shows the earliest effect of exploitation. Residual gravity decreased in the production zone and increased a little in the reinjection zone. From June 1996 to August 1997 (Fig. 8(b)), the residual gravity increased in the production zone, but there was little change in the reinjection zone. The residual gravity increase in the production zone shows net mass gain by rapid recharge of geothermal fluid from surrounding areas. In addition, both maps show 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 in the basin structure of the Usa Group (Hayashi et al., 1988). The mass movement associated with the production of the geothermal fluid occurred in this basin structure.

5. CONCLUSIONS

Repeat gravity measurements were started in 1991, before the commencement of the production and reinjection at the Takigami power station. From the results of these measurements, we estimated the background gravity change caused by seasonal changes of shallow ground water level using a multivariate regression model relating gravity to precipitation. The accuracy of the background gravity changes is about ±10 microgals.
We used the correlation to eliminate the effect of the background gravity change. Residual gravity increases of up to 10 microgals were detected in the reinjection zone, and residual gravity decreases of up to 40 microgals 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.

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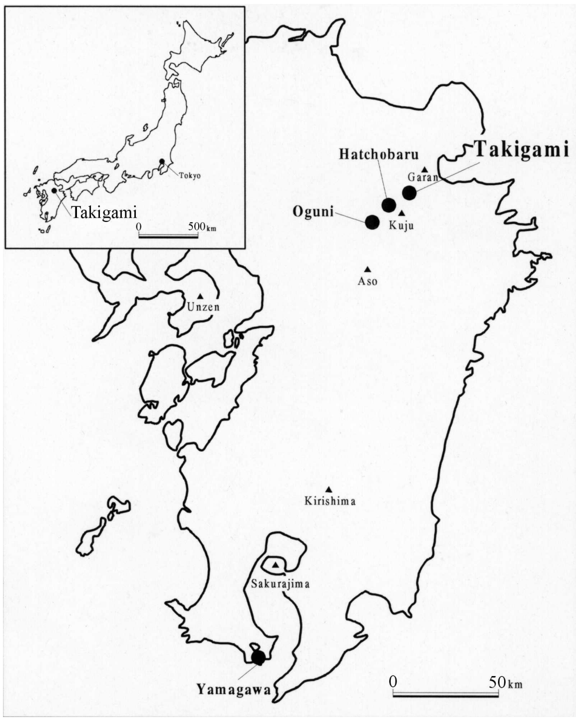

Figure 1. Location of the Takigami geothermal field.

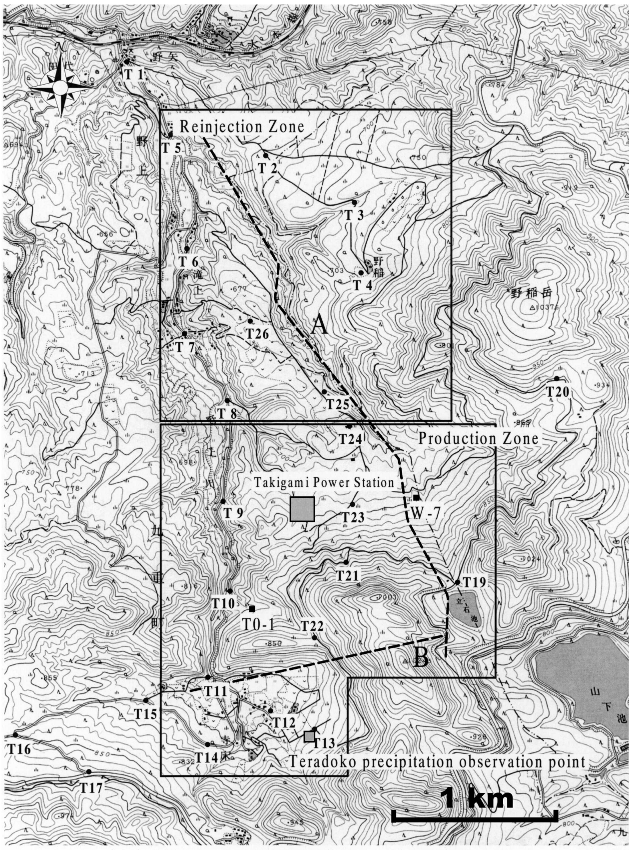

Figure 2. Distribution of the observation stations (T1 to T27) for the repeat gravity measurement. Broken lines A and B indicate the Noine Fault and the Teradoko Fault, respectively.

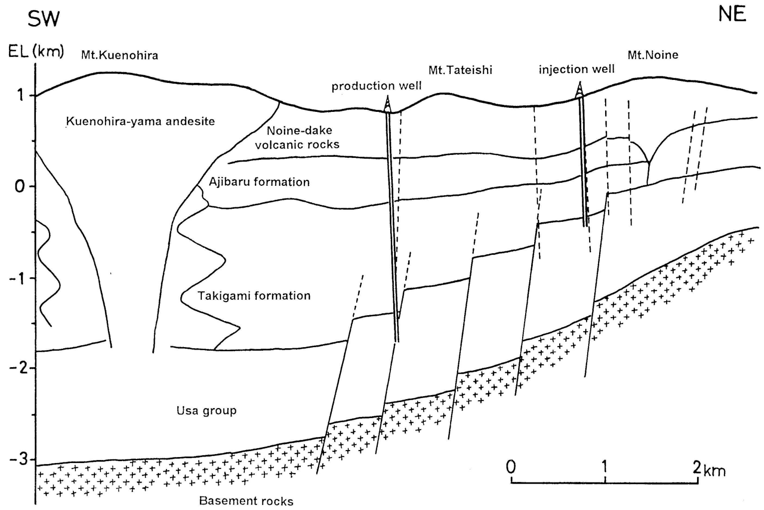

Figure 3. Schematic geological SW-NE cross-section of the Takigami geothermal field (Hayashi et al., 1988).

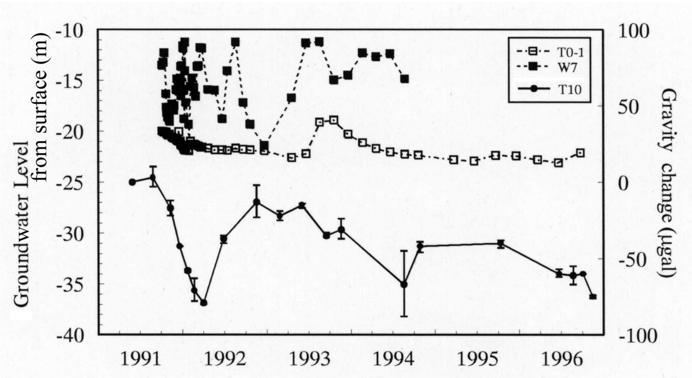

Figure 4. Changes in the groundwater level at Well TO-1 and Well W7, and gravity changes at Station T10. An Error bar on each gravity plot indicates a difference between the value of the first half and that of the second half of the two-way measurement.

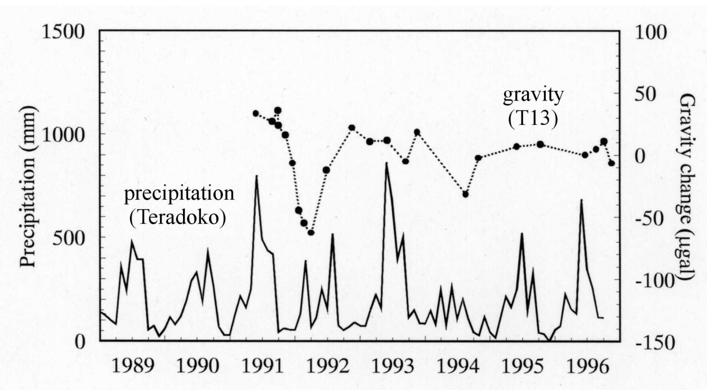

Figure 5. Comparison between precipitation and gravity at Station T13.

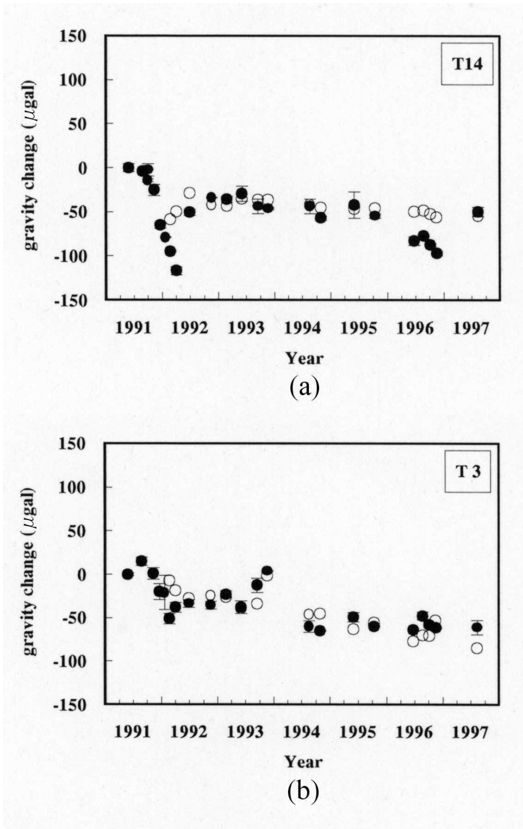

Figure 6. Comparison between the observed and calculated gravity changes. (a) the production zone (b) the reinjection zone. Solid circles are observed and open circles are calculated. Error bars indicate the same values as those in Fig. 3.

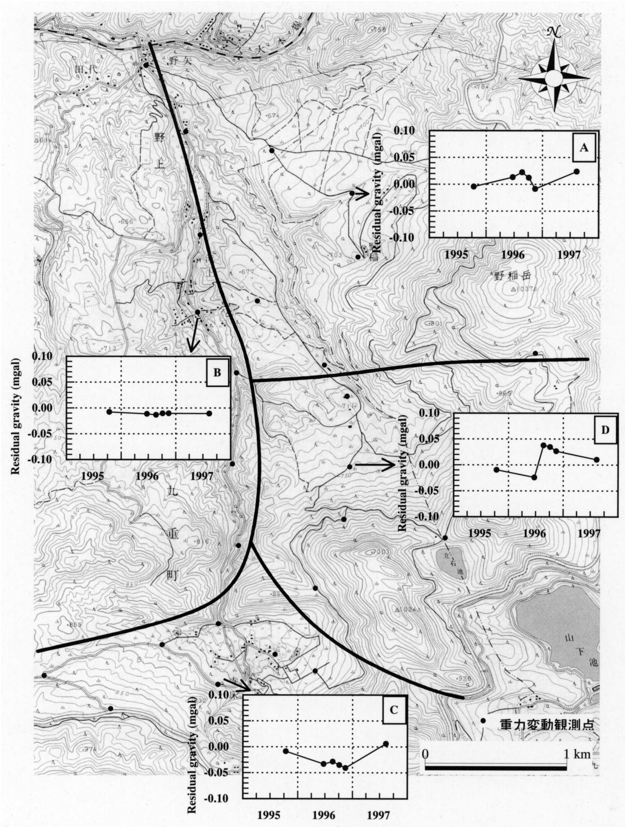

Figure 7. Typical patterns of residual gravity change at the difference areas in the Takigami geothermal field.

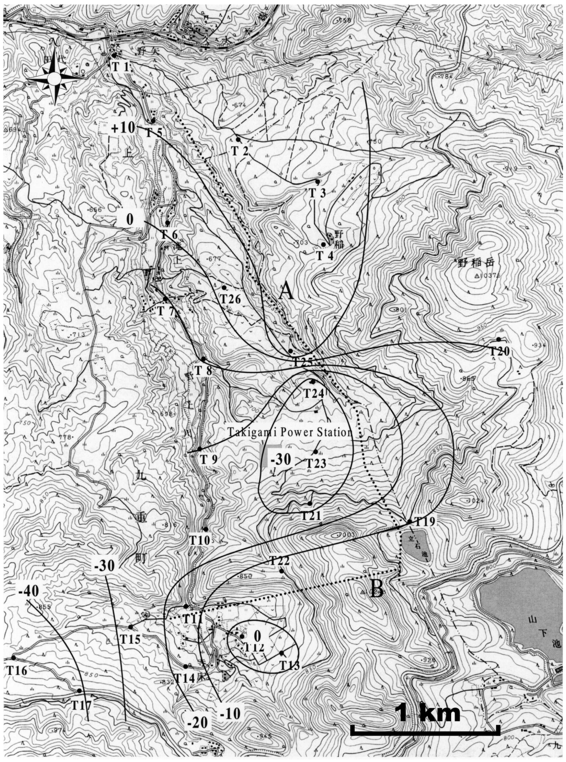

Figure 8(a). Contour map of the gravity changes at the Takigami geothermal field from October 1995 to June 1996. The effects of groundwater level changes have been eliminated.

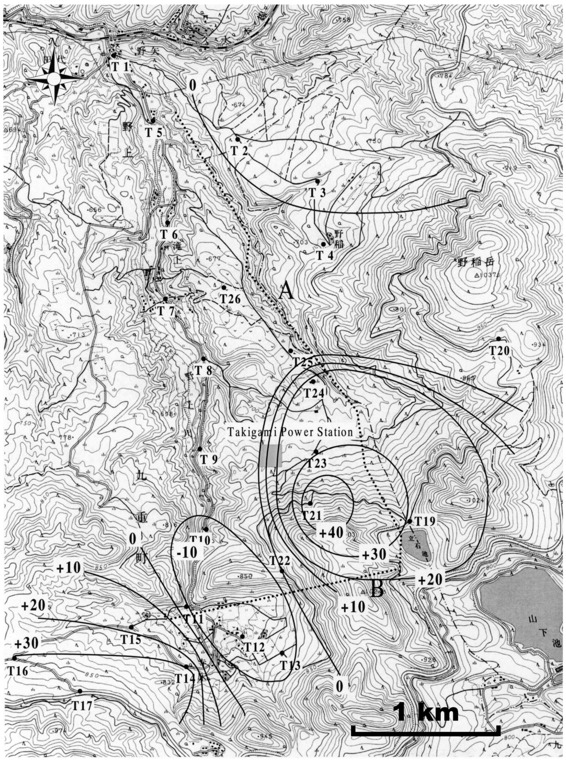

Figure 8(b). Contour map of the gravity changes at the Takigami geothermal field from June 1996 to August 1997. The effects of groundwater level changes have been eliminated.