# Reservoir Monitoring by Observation of Gravity Changes at the Takigami Geothermal Field, Central Kyushu, Japan

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## ABSTRACT

Repeat gravity measurement have been conducted at the Takigami geothermal field in Kyushu, Japan in order to monitor the underground geothermal fluid flow system. Gravity changes at 26 stations have been monitored since May 1991 to study reservoir behavior. The observed gravity changes included gravity changes due to shallow ground water level change. We removed the effect of shallow ground water level change on gravity by applying a statistical technique 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 November 1996. Multivariate regression analysis was applied in order to establish the relationship between gravity and precipitation; a good correlation was obtained. Therefore, it is now possible to estimate the gravity change due to ground water level change at each observation point by using the precipitation data collected prior to the gravity measurement. We thereby define the residual gravity, which is the observed gravity minus this estimated gravity. The results of repeat gravity measurement show that repeat gravity surveys is an effective method to monitor the underground hydrological systems.

## Introduction

Mass fluid movement is caused by the production and reinjection of geothermal fluid in geothermal fields. These mass redistributions can cause measurable gravity changes at the surface of the earth. Repeat gravity measurements have been carried out in some geothermal fields. Gravity decreased about 1000mgal after 30 years in the Wairakei geothermal field, New Zealand (Allis and Hunt, 1986).

On the other hand, 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 qualitative 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.

We started the repeat gravity measurement at the Takigami geothermal field before the geothermal exploitation. We estimated the background gravity change that is caused by the seasonal changes of the shallow groundwater level using statistical methods. We applied a multivariate regression model and eliminated the effect of shallow groundwater level change in order to extract the gravity change associated with the production and reinjection of geothermal fluid.

## Repeat gravity measurement

Takigami geothermal field is located in the southwestern part of Oita prefecture, central Kyushu, Japan (Figure 1, overleaf). The Takigami power station (25MW) was completed in November, 1996. The observation points for repeat gravity measurements are shown in Figure 2 (overleaf). We used Scintrex CG-3 and CG-3M gravimeters to measure precise gravity change around The Takigami geothermal power station. The repeat gravity measurements were conducted from May 1991 to July 1998 at specified intervals (one to three months). The two-way measurement method was taken to evaluate the instrumental drift and precision. We estimated the errors of observation as –10 mgal.

## Multivariate regression model

It is necessary to estimate the effect of shallow groundwater changes to detect changes in deep geothermal fluid flow by the repeat gravity measurement.

By extending the theory of the autoregressive model (Koike et al., 1991), a multivariate regression model is constructed relating the changes of shallow ground water level to gravity changes:

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

where $y_t$ is a criterion variate, $x_t$ is an explanatory variate with $\beta_i$ the coefficient of regression, m is an optimum degree of fit, $\varepsilon$ is white noise.

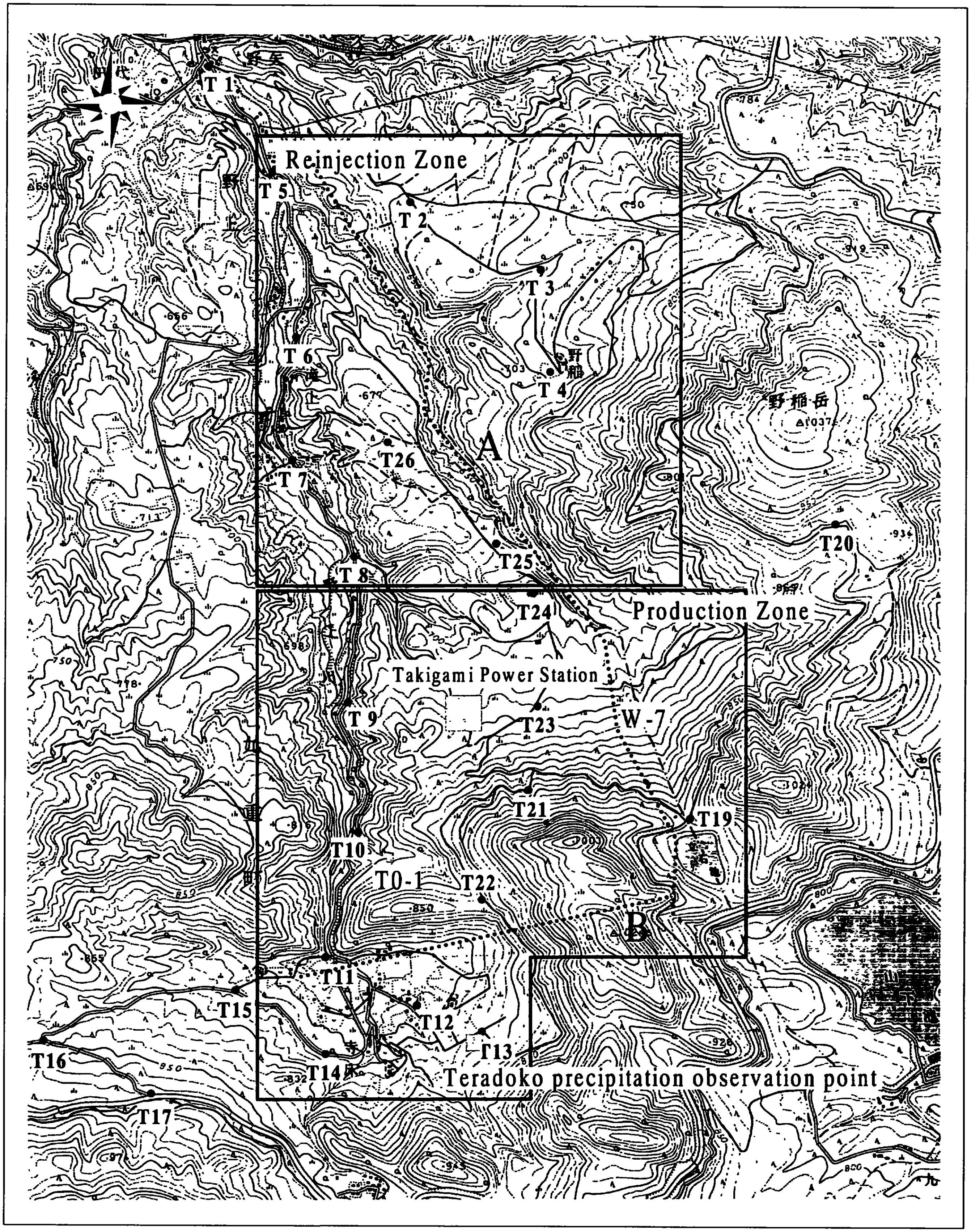


**Figure 2.** Distribution of observation points (No. 1 to 27) for the repeated gravity surveys at Takigami geothermal field. Broken lines A and B show Noine fault and Teradoko fault, respectively. The production and reinjection zones are in the southern and northern part of this field, respectively.

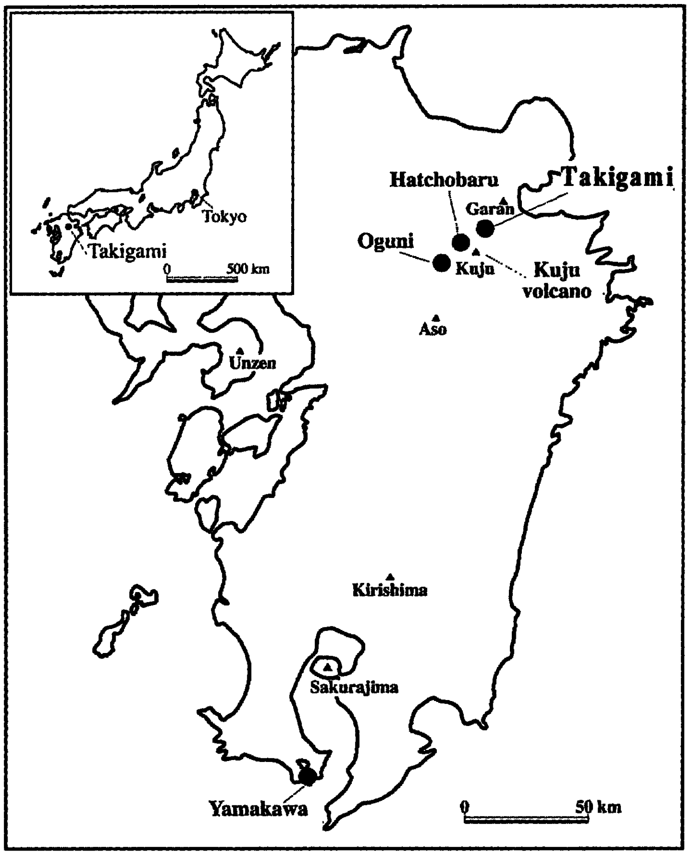


**Figure 1.** Location map of the Takigami geothermal field, central Kyushu, Japan.

At first, we intended to construct the multivariate regression model relating change of groundwater level with gravity. Figure 3 shows the changes of gravity (at T10) and groundwater level (in wells T0-1, W-7). Although long-term trends are clearly correlated, the high-frequency content obviously differs. Although these two observation wells are adjacent, the groundwater levels are significantly different in phase and amplitude. For this reason, there is the possibility that the groundwater level change is controlled by local hydrological structure. Therefore, we tried to correlate gravity with precipitation, which is believed to control the groundwater level change of this area.

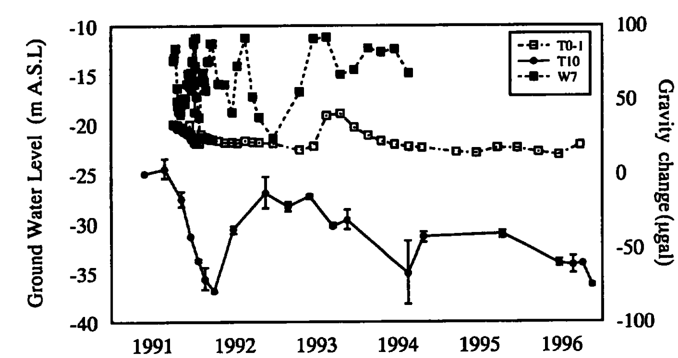


**Figure 3.** Changes in the ground water level at Well T0-1 and Well W7 and gravity changes at T10.

Figure 4 shows the comparison between precipitation and gravity. When we examine the correlation of gravity and precipitation, a phase lag of about 3 months exists. However, there is good correlation (over 0.7) when we shift the phase contrast and calculate the coefficient of correlation. Therefore, we quantitatively estimated the effect of background gravity change using a precipitation-gravity correlation.

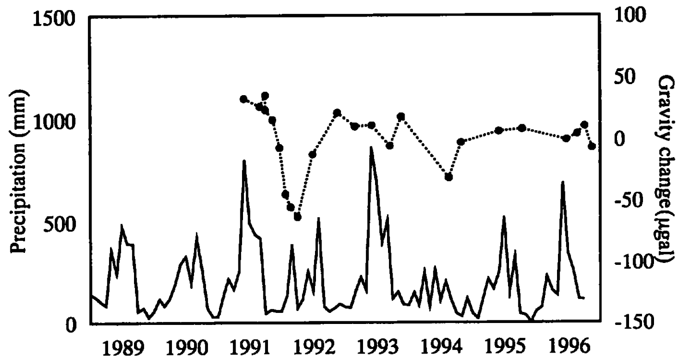


**Figure 4.** Comparison between precipitation and gravity. Long-term trend subtracted from gravity.

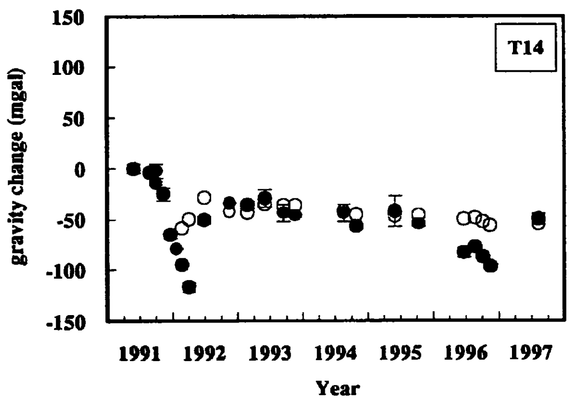


**Figure 5a.** Comparison between the observed and estimated gravity changes at the Takigami geothermal field in the production zone.

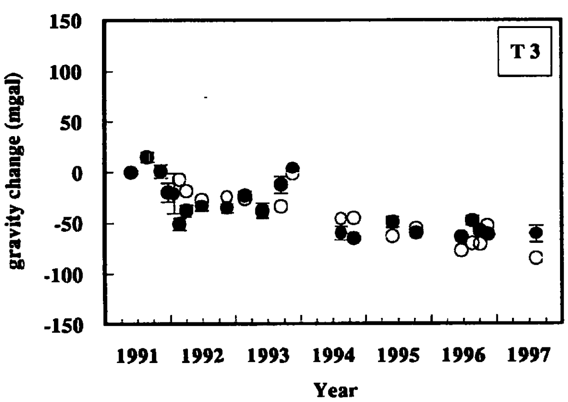


**Figure 5b.** Comparison between the observed and estimated gravity changes at the Takigami geothermal field in the reinjection zone.

Two examples of comparison between the observed and estimated gravity in the production and reinjection zones are shown in Figure 5. 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 measurement. The estimation accuracy of the background gravity is ±10mgal. Before exploitation, there is good agreement between the observed and estimated gravity. However, there are differences up to 40 mgal 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.

## Discussion

The residual gravity (due to reservoir effects), taken as the difference between observed and estimated gravity at each observation station can be subdivided into four types of response is shown in Figure 6, from October 1995 to August 1997.

### *Type A*

This type of gravity change response is seen around the reinjection zone located in northern part of observation area. Just after the reinjection of the geothermal fluid begins, gravity increases, and it decreases from the summer of 1996 through fall. After that, residual gravity increases once again from the autumn of 1996 through the summer of 1997.

### *Type B*

As soon as the production and reinjection of the geothermal fluid begins a slight decrease of the residual gravity is seen. However, residual gravity hardly changes afterwards.

### *Type C*

This type of response is seen at observation points located in the production zone along the Teradoko fault, in the southern part of the observation area. Gravity decreases from the onset of production until November 1996, stabilizes, then starts 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 was seen immediately after the geothermal fluid production started, and between June and August 1996 gravity increased sharply. After that, residual gravity gradually decreased.

In summary, the decrease of the residual gravity was seen in the production zone and increase of the residual gravity was seen in the reinjection zone just after the production and reinjection start of the geothermal fluid.

Two contour maps of residual gravity changes are shown in Figure 7 (a) and (b). The gravity change from October 1995 to June 1996 is shown in Figure 7 (a). At the end of this period, production and reinjection of the geothermal fluid began. Figure 7 (a) also shows the earliest effect of exploitation. The residual gravity decreased in the production zone and increased a little in the reinjection zone. The gravity change from June 1996 to August 1997 is shown in Figure 7 (b). The residual gravity increase in the production zone, but it did not change so much in the reinjection zone. The residual gravity increased in the production zone shows net mass gain by rapid recharge of the geothermal fluids 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 into the basin structure (Hayashi et al., 1988). The mass movement associated with the production of the geothermal fluid occurred in basin structure.

## Conclusion

We started repeat gravity measurements about 5 years ago before the production and reinjection at Takigami began. Based on these result, we estimated the background gravity change that is caused by seasonal changes of shallow ground water level by using the multivariate regression model relating gravity to precipitation. As a result, we were able to estimate the back ground gravity change with an accuracy of ±20mgal. We can use the correlation to eliminate the effect of the background gravity change. Residual gravity increases of up to 10 mgal 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 relating low production rates like Takigami.

## References

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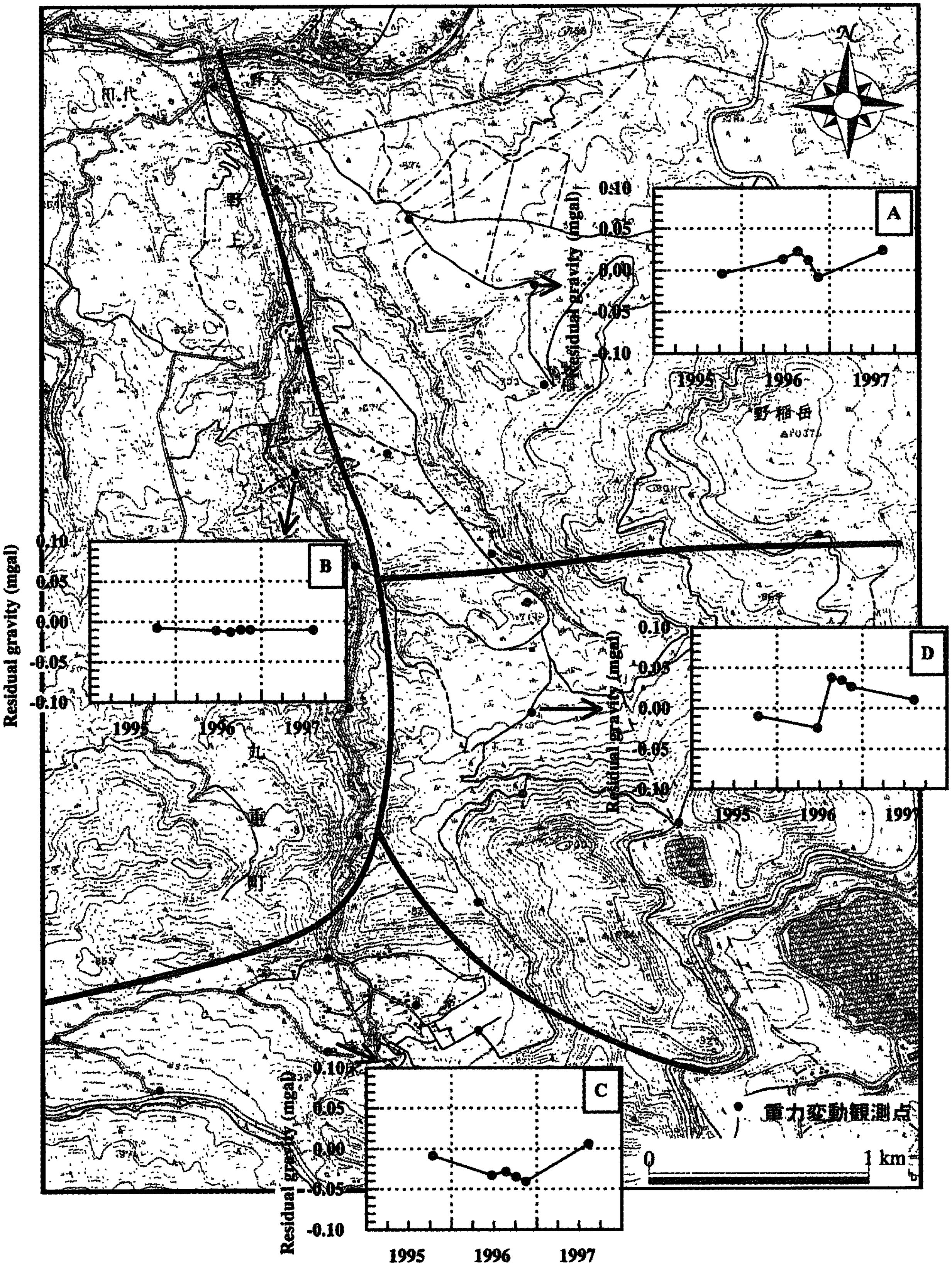


**Figure 6.** Typical patterns of residual gravity change with time in different areas in the Takigami geothermal field.

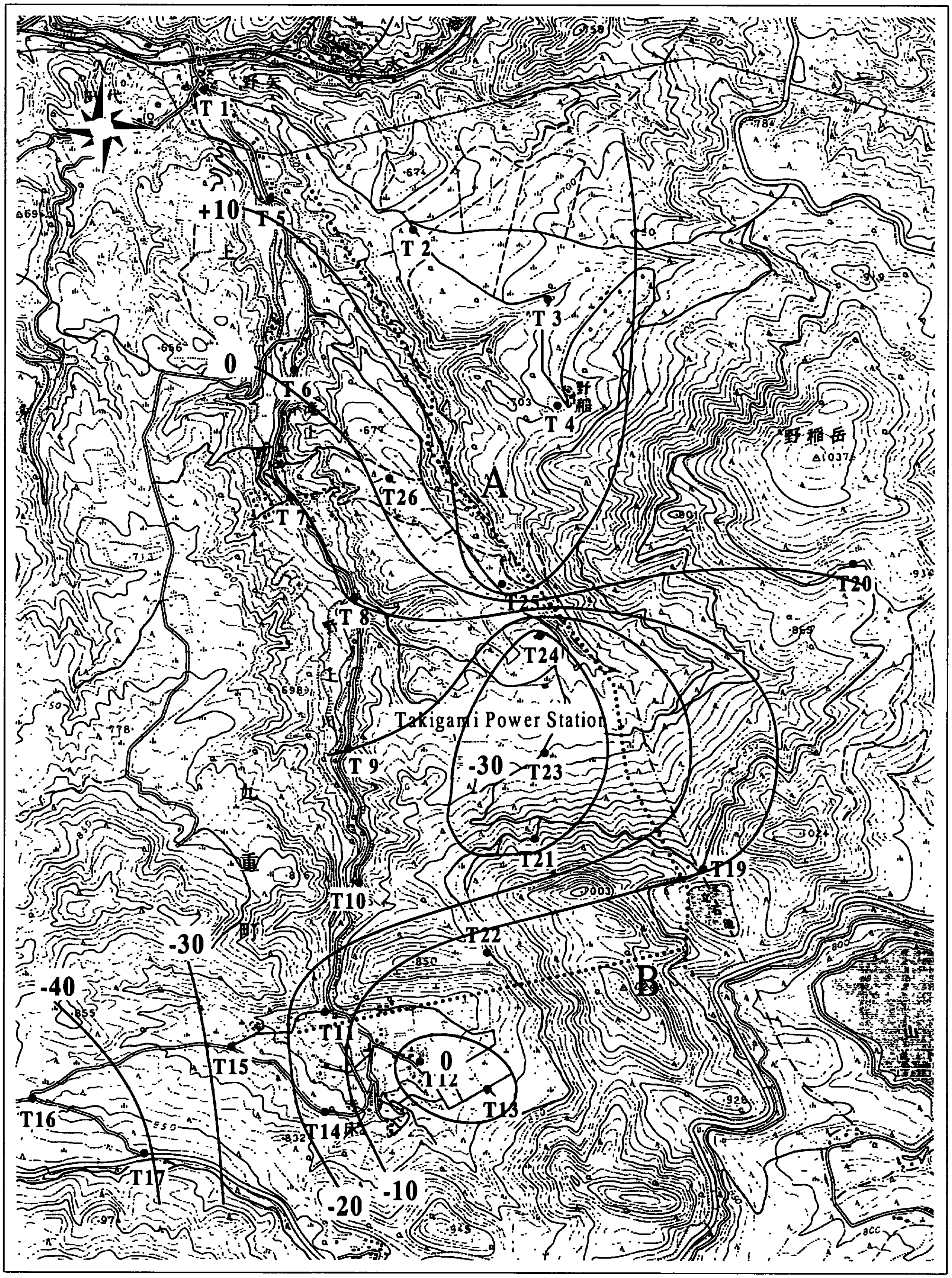


**Figure 7 (a).** Contour maps of the gravity changes, for which the effect of precipitation has been eliminated, at the Takigami geothermal field from October, 1995 to June, 1996.

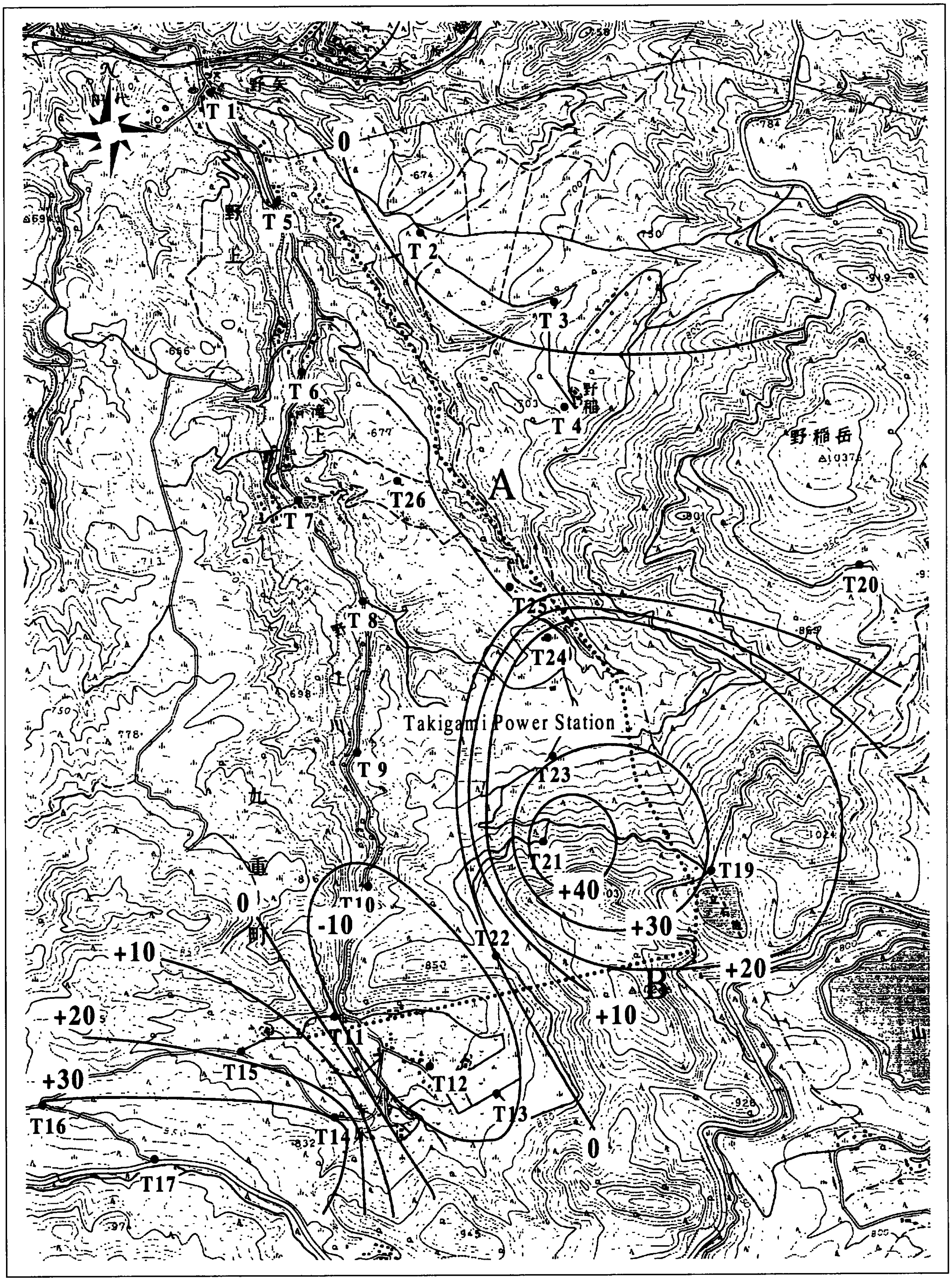


**Figure 7 (b).** Contour maps of the gravity changes, for which the effect of precipitation has been eliminated, at the Takigami geothermal field from June, 1996 to August, 1997.