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EVALUATION OF MICROGRAVITY BACKGROUND AT THE UNDISTURBED OGUNI GEOTHERMAL FIELD, JAPAN

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ABSTRACT

Repetitive microgravity monitoring surveys are planned to help characterize reservoir behavior after electric power generation begins at Oguni in 2002. To prepare for this monitoring program, background microgravity has already been surveyed numerous times at Oguni. Seasonal changes in gravity have been observed. The observed background temporal changes in microgravity are believed to be due primarily to variations in the depth of the shallow ground water table. To separate the effects of water table fluctuations from those caused by events in the deep reservoir, we first tried to correlate both gravity changes and water table level changes with precipitation at a particular benchmark where the water level and microgravity histories were both known. Next, the resulting correlation was used to compute the effect of precipitation on microgravity elsewhere in the field, and the results were compared with measurements. Observed excursions in microgravity are somewhat greater than those estimated in this manner.

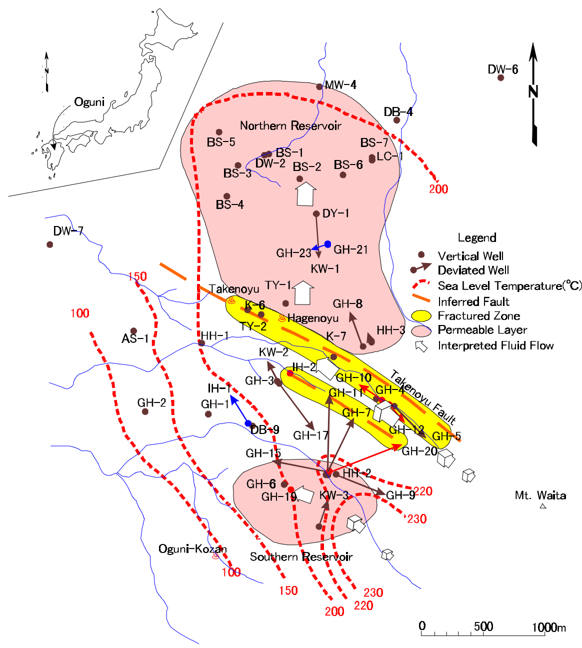

Figure 1. Location and extent of the Oguni geothermal field in Kyushu, Japan

INTRODUCTION

The Oguni field is located in central Kyushu, southwestern Japan (Figure 1). The permeable reservoir area (established by drilling logs and pressure-transient testing) is approximately 4 km (north-south) by 2 km (east-west), and a cap rock is present between approximately 300 m RSL and 750 m RSL. Below the cap rock, temperatures range from 200°C to 240°C and a small steam zone is present at the top of the reservoir. A shallow unconfined ground water aquifer is present above the cap rock. The water table is about 100 m deep in the northern part of the field (Abe et al., 1995). A 20 MW_e (gross) double-flash geothermal power plant will soon be constructed by Electric Power Development Company (EPDC) on the northwestern flank of Mt. Waita (1500 m RSL), in the southeastern part of the area.

Repeat gravity surveys will be performed in the future at regular intervals to help understand reservoir behavior during field exploitation. Nakanishi et al. (1998) estimated the changes in gravity which are likely to be caused by exploitation using a numerical simulation technique. Their results suggest that, after 30 years of operation, slight gravity increases (about 35 μgal) will occur in the main reinjection wellfield to the north. Relatively large gravity decreases (about –130 μgal) centered on the middle of the production wellfield are also predicted, caused by production-induced local pressure decline and associated boiling (Figure 2). Since these predicted gravity disturbances are rather small, accurate measurements will be required and careful noise reduction techniques must be employed.

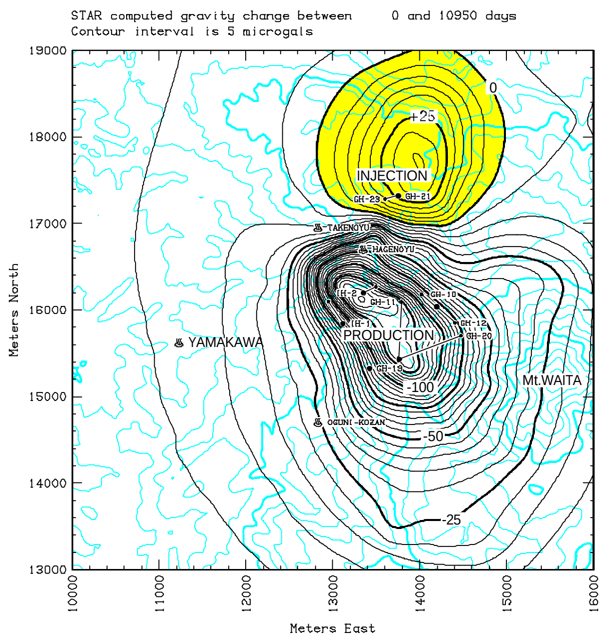

Figure 2. Calculated gravity changes caused by 30 years operation of the 20 MW_e Oguni geothermal power plant

At Oguni, large and rapid changes in the water table depth take place because of the mountainous terrain and the relatively heavy local precipitation. Between 1990 and 1999, natural water table depth fluctuations (attributable to rainfall) exceeded 16 meters. Consequently, microgravity changes caused by water table fluctuations are likely to represent a significant fraction of the total measurable temporal gravity signal. If the "noise" introduced by water table variations could be compensated for directly, based on rainfall records, corrections could be applied in areas where no observation wells are present. This method can also help compensate for the effects upon gravity of changes in water saturation in the vadose zone.

PROCEDURE

Precise gravity observations

A total of 41 benchmarks have been established for gravity monitoring in the Oguni geothermal field (Figure 3), lying at elevations between 519 and 1095 m RSL. The benchmarks were situated in locations where substantial gravity changes due to reservoir disturbances caused by geothermal power plant operations are expected, based on forecasts using the STAR reservoir simulator and surface gravity postprocessor (Pritchett, 1995) – see Figure 2.

We started precise gravity observations in May 1996 and continued for about 3 years, measuring gravity monthly at each of the 41 benchmarks relative to a reference benchmark located about 11 km from the geothermal field. The Geographical Survey Institute (GSI) maintains this first-order leveling benchmark used for reference. The reference benchmark is far enough from the geothermal field that exploitation-induced gravity changes are not expected.

A CG-3M gravity meter was used to measure gravity. This gravity meter was calibrated to yield relative gravity difference from the reference point. Precise leveling surveys have been conducted twice during the period of gravity measurements, and indicate that ground surface elevation changes were less than the ability of the leveling network to measure them. Consequently, gravity changes caused by earth subsidence or swelling were completely negligible.

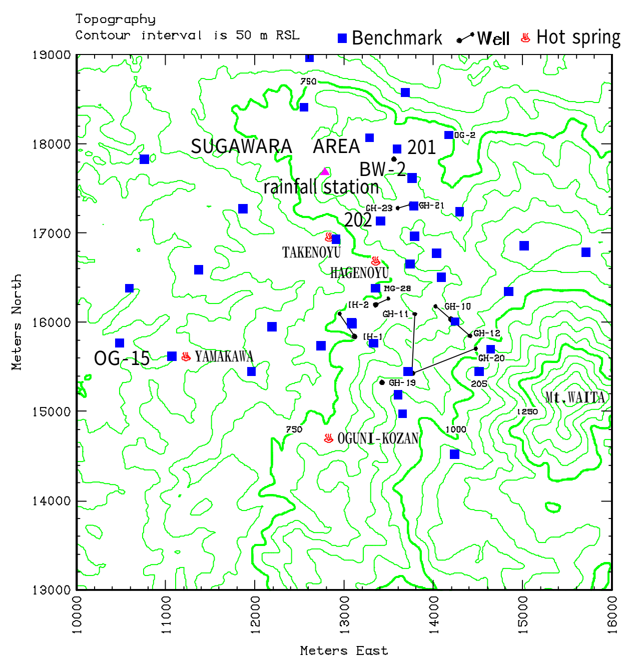

Figure 3. Location map of measurement area, measurement benchmarks, observation wells of shallow ground water table and rainfall measurement station

Estimating water table changes from rainfall data

Precipitation measured in the northern part of the Oguni field is shown in Figure 4, together with the history of the measured water level in shallow observation well BW-2 (near benchmark 201).

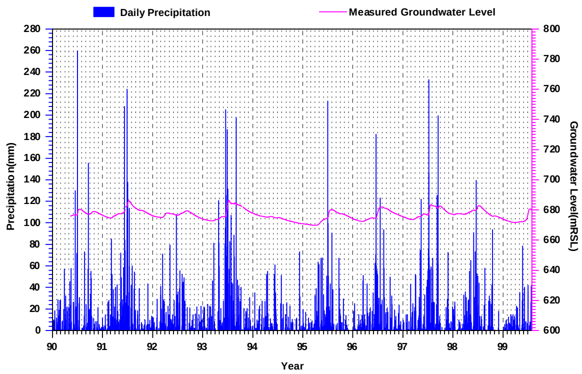

Figure 4. Precipitation and ground water level changes measured in shallow well BW-2

Rainfall is heavy at Oguni. Annual total rainfall has varied between 1130 and 3450 mm during the past decade. Average annual rainfall is 2250 mm. Well BW-2 was drilled to observe the shallow unconfined water table above the cap rock. Overall, the range of water level excursions in BW-2 was 16.9 meters during this period. Increases in ground water level in this well clearly correspond to rainfall (Figure 4). When a rainstorm occurs, the water level in the well first increases suddenly and then decreases gradually. Accordingly, an empirical exponential decrease equation (Yuhara and Seno, 1969) was used to correlate precipitation with water level in the well:

$$H(t) = H_1+\alpha\Sigma_n R_n \exp\{-c(t-t_n)\} \qquad (1)$$

where H_1 is an initial ground water level before rainfall, t represents time, α and c are constants, and R_n is the precipitation (mm) which falls on day t_n.

Calculation of gravity change from precipitation

Using the above relation to obtain water table depth changes from precipitation data, we next calculate the resulting gravity changes using the relationship of Allis and Hunt (1986);

$$\Delta g=2\pi G\phi\rho_w\Delta h \qquad (2)$$

where Δg is the gravity change (μgal = 10^{-8} m/s^2), G ($6.67\times10^{-11} m^3kg^{-1}sec^{-2}$) is the universal gravitational constant, ϕ is the porosity near the water table depth, ρ_w is the density of ground water (kg·m^{-3}), and Δh is the change in water level (m). Several shallow observation wells distributed widely in the northern Oguni area exhibit similar ground water table elevations (relative to sea level). This suggests that the infinite-plane approximation implicit in Eq. (2) is appropriate, at least for the northern part of the field.

RESULTS

To illustrate representative results, long-term gravity change histories measured at benchmarks 201 and OG-15 are shown in Figure 5 and 6, respectively. Locations of these benchmarks are indicated in Figure 3. Gravity changes at station 201 are substantial, consisting mainly of large abrupt shifts in November 1996 and November 1998 which interrupt a history that is otherwise relatively smooth and continuous. The reasons for the abrupt gravity discontinuities are not known. By contrast, the Benchmark OG-15 measurements exhibit relatively small fluctuations and regular seasonal changes. The large shifts that occurred at benchmark 201 were not observed at OG-15.

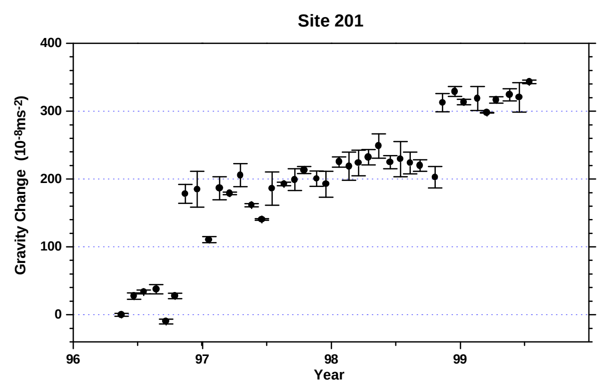

Figure 5. Measured changes in surface microgravity at benchmark 201. Note the step changes in late 1996 and 1998.

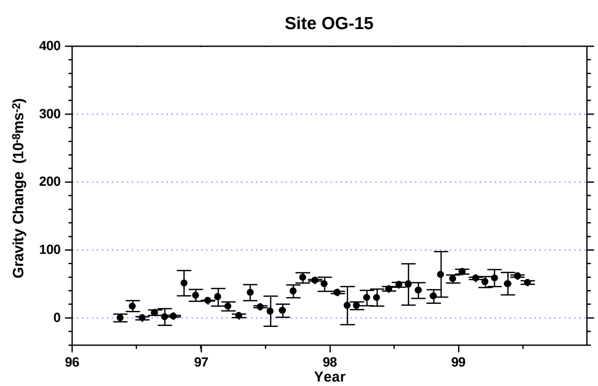

Figure 6. Measured changes in gravity at benchmark OG-15.

Differences in absolute gravity acceleration among the various 41 benchmarks arising from elevation differences alone exceed 130,000 μgal. The amount of overall temporal gravity variability that was observed at each benchmark seems to be proportional to the difference in absolute gravity acceleration between the benchmark in question and the reference benchmark. Therefore, we suspect that systematic errors are involved, caused by measurement or data processing problems. Data analysis was therefore limited to the stable period between the two large shifts.

Applying equation (1) to the rainfall data and the water level measured in well BW-2, a least-squares fitting procedure yielded the following optimum values for the free parameters:

H_1=671 (m RSL), α=0.00937 and c=0.00990 (day^{-1})

The ground water level history calculated using these parameters is compared with the actual water level measurements in Figure 7. The porosity at the ground water level was estimated to be 0.11 by least-squares correlation of measured water level changes with gravity changes. This value is reasonable for the shallow ground water aquifer in the area. The gravity change history that was calculated based on the inferred changes of water table depth is shown in Figure 8 together with the gravity changes observed at station 201. On the whole, the general features of the observed gravity history are reproduced by the calculation. Next, however, we applied the same technique to nearby station 202. As figure 9 shows, the resulting calculated gravity history does not correlate very well with measured values, although both benchmarks are obviously located on the same unconfined ground water system and would therefore be expected to exhibit similar water table depth histories and resulting microgravity changes.

DISCUSSION

Gravity changes have been observed at all 41 Oguni benchmarks. The overall amplitudes of the gravity changes are relatively large in regions of high ground surface elevation, and the observed changes increase in proportion to the difference in absolute gravity acceleration between the station in question and the distant reference benchmark. The most stable benchmark (OG-15) has the smallest absolute gravity difference from the reference point. We have also carried out simultaneous comparative measurements using a second gravimeter, and very similar results were obtained. However, the slight difference in gravity values obtained from the two gravimeters also appears to be in proportion to station elevation. For that reason, we believe that the gravimeter calibration was insufficient for the accuracy requirements of this program. Additional and more precise calibrations need to be carried out using additional reference benchmarks to cover the entire absolute gravity range prevailing in the Oguni field.

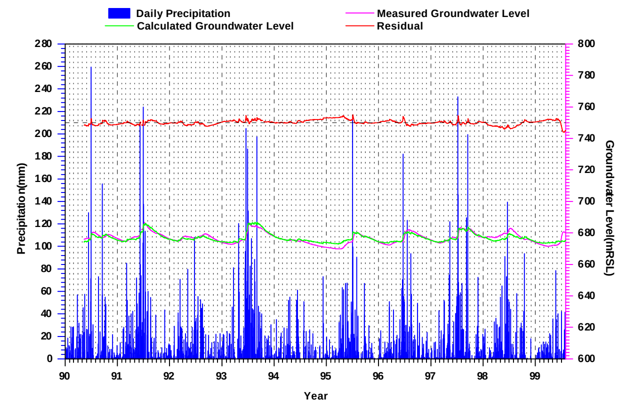

Figure 7. Precipitation and ground water table in well BW-2

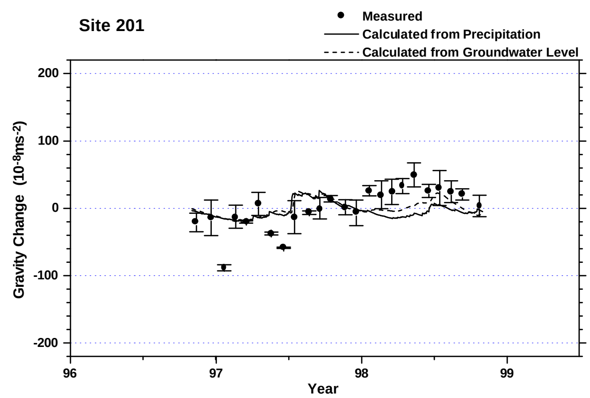

Figure 8. Comparison between observed and calculated gravity values at benchmark 201.

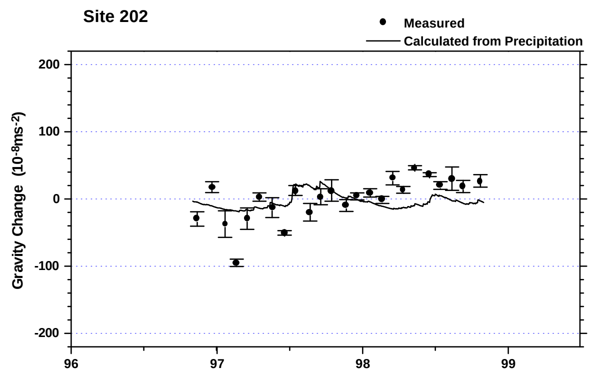

Figure 9. *Comparison between observed and calculated gravity values at benchmark 202.*

To further improve the accuracy of the measurements, the gravity history at the reference benchmark should be more completely characterized. Alternatively we can connect an absolute gravity point to the reference benchmark with a relative gravity meter. The reference benchmark should be located where the gravity is expected to be sufficiently stable.

An imperfect correlation was observed between ground water table fluctuations and temporal gravity changes at Oguni. Continuous gravity measurements appear to be necessary during periods of rapid change in ground water table caused by heavy rainfall. Ten meters of water table level change can occur at Oguni within a few months. If continuous gravity monitoring were carried out at a few representative stations at Oguni, gravity changes caused by ground water table changes could be better characterized. The potential value of continuous microgravity monitoring for geothermal reservoirs has been shown by Sugihara (1999). Of course, the situation is likely to be more promising at other geothermal sites with less rainfall.

SUMMARY

Temporal changes in microgravity have been monitored during a three-year period prior to the onset of Oguni geothermal field exploitation, while human activities at the site were at a minimum. Ground water table changes are believed to be the primary reason for the observed gravity fluctuations. We attempted to establish a relationship between ground water level and gravity, but a good correlation was not obtained. On the other hand, marked temporal microgravity changes were detected at several benchmarks. We recommend that continuous microgravity monitoring be carried out in the future, at least at a few representative stations. Accurate delineation of changes in gravity at the reference benchmark will be essential for precise characterization of the changes in gravity with time at the Oguni geothermal field.

ACKNOWLEDGEMENTS

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