CONTINUOUS GRAVITY MEASUREMENTS AT WHAKAREWAREWA GEYSER FLAT

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SUMMARY - We made continuous gravity measurements at Whakarewarewa Geyser flat using a Scintrex CG-3M gravimeter and detected particular signals whose amplitude are about 10 microGal. This gravity change cannot be explained by the water levels variations in Te Horu pool, but is interpreted to be mainly brought about by changes in water level and steam distribution within the underground reservoir. There are no visual records of geyser activity over the period of our measurements, so we cannot correlate the relationship between the observed signals and the dynamic sequence of geysering. These measurements represent a pilot study for an elaborate gravimetric survey.

1 INTRODUCTION

Geyser activities are unstable processes that transfer water and heat from an underground reservoir to the Earth's surface. The physical mechanisms that cause geysering are not well known due to the difficulty in obtaining information regarding the subsurface geometry and mechanics of subsurface processes. Assuming the flash boiling model as a mechanism which results in geyser eruptions (Figure 1), changes in water level and/or the steam fraction in the reservoir are important.

Local gravity changes of episodic character in time and space, therefore, may occur during the geysering process. In order to test for this we applied the gravity monitoring technique to obtain information on the geysers at Wakarewarewa Geyser flat, New Zealand.

Long-term changes, which evolve over months and years, can be monitored by gravity measurements (in profile or plan) at regular intervals. Such measurements have been made in geothermal fields during exploitation and have produced useful information (e.g. Hunt and Kissling, 1994

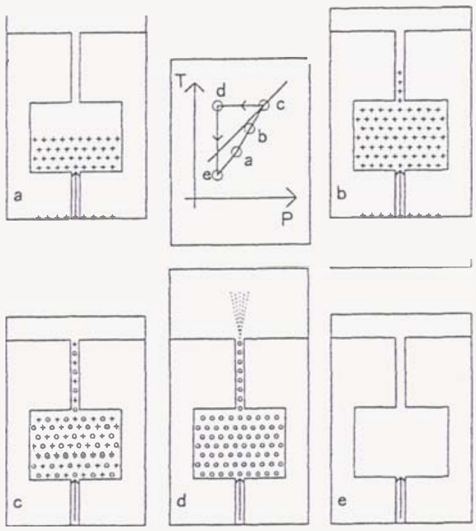

Figure 1- A diagram illustrating the sequence of events in a geyser system which leads to flash boiling and eruption of a column of water (simplified from Sparks et al., 1997).

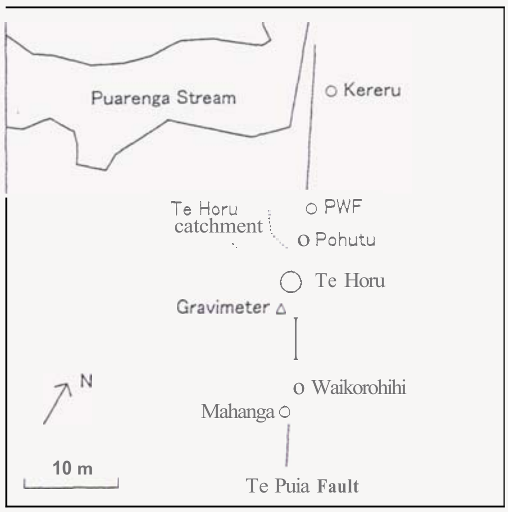

Figure 2- Map showing location of Whakarewarewa Geyser Flat, New Zealand. The dotted line represents the catchment area draining into Te Horu.

2. WHAKAREWAREWA GEYSER FLAT

Most major geysers seem to act independently of one another even when closely located (Rinehart, 1980). However, the geyser complex on Whakarewarewa Geyser flat displays an elaborate multi-vent structure with complex discharge behavior. Seven active vents which are part of the geyser complex are shown in Figure 2. They lie along the Te Puia fault: Kereru, Prince of Wales Feathers (PWF), Pohutu, Te Horu, Waikorohihi, and Mahanga. Te Horu is a cauldron-like cyclic hot spring and the others are geysers. With the exception of Kereru, all of these vents lie about 7 meters above the present height of Puarenga Stream. Other studies have shown there are close relations among the activities of Te Horu cauldron and the three geysers, that is, Pohutu, PWF and Waikorohihi (Lloyd, 1975; Weir et al., 1992). The typical eruptive sequence is as follows: PWF always accompanies and usually precedes Pohutu. Eruptions from Waikorohihi are usually followed by eruptions from the PWF and later Pohutu. The water in Te Horu is always rising when Pohutu starts to erupt (Figure 3). An arrangement of surface openings, underground channels, and reservoirs which can account for the above geyser and pool behavior and the results of Lloyd's dye tracing experiment (Lloyd, 1975) is illustrated in cross section (Figure 4).

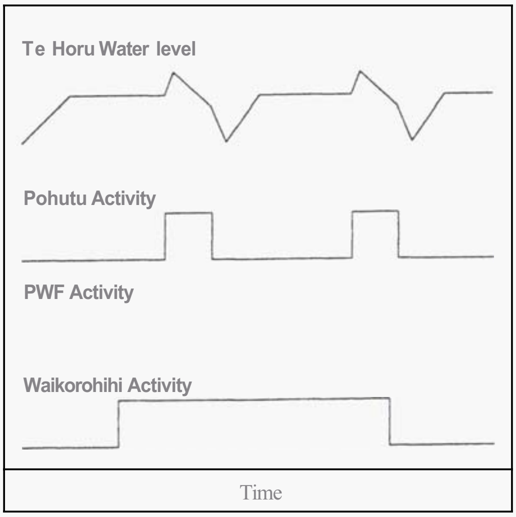

Figure 3- Schematic diagram of regular geyser behavior, the relation of Te Horu water level and activities of the three geysers.

The model suggests that maintenance of airfall recharge water to Te Horu from Pohutu during the eruptions of the latter is essential for the continued operation of the geyser system. The importance of the wind direction on the activity was explained in detail by Weir et al. (1992). Only Pohutu contributes to the recharge of Te Horu in any large amount. During the splashing mode of Pohutu, most of the erupted water drains into Te Horu, but during a full column eruption the fraction of Pohutu airfall water entering Te Horu depends on wind conditions. The proportion of airfall reaching Te Horu varies with the wind direction. Low Te Horu water levels are associated with a dominant west-south-west component of wind speed, which tends to direct Pohutu's plume away from the catchment area of Te Horu (Figure 2). Low water levels in the Te Horu cauldron were found to be associated with a rapid and irregular cycle of geyser activity. Conversely, high water levels produced a more stable eruption pattern, with longer eruptions, as well as longer intervals between eruptions.

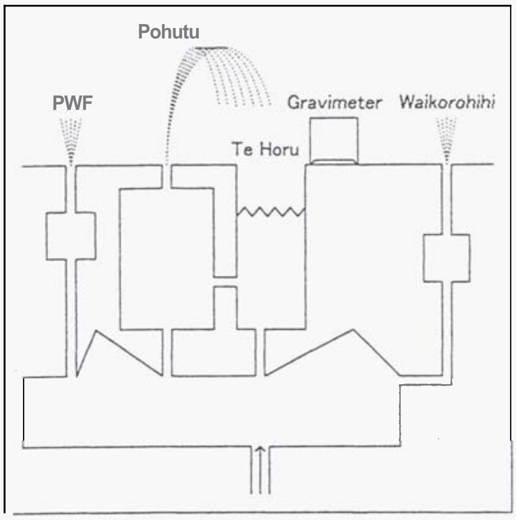

Figure 4- Inferred cross section along the Te Puia fault through Pohutu and nearby geysers (adapted from Lloyd, 1975).

3. MEASUREMENTS

We used a microprocessor-based automated spring gravimeter, Scintrex CG-3M gravimeter, which was released about ten years ago. The gravimeter can be operated either in field mode or in cycling mode. In cycling mode data acquisition is triggered at a pre-defined sampling rate. We can make measurements continuously in the cycling mode and set the sampling rate to be 1 point per minute or faster. Bonvalot et al. (1998) show the benefits of the Scintrex model in making continuous measurements for volcanic monitoring, and Sugihara (1999) shows similar benefits for geothermal reservoir monitoring.

We carried out continuous gravity measurements at Whakarewarewa on 20 February 1997. We acquired 52 mean values of the 60 seconds sampling using a Scintrex CG-3M gravimeter (serial #270). The gravimeter was set inside a plastic container to protect it from geyser spray, at a place near to Te Horu pool (Figure 2). The water level in Te Horu pool was monitored with a probe designed to measure pressure inside the water column.

CG-3M has an in-built function to correct for the Earth-tide effect using the formulae given by Longman (1959). We did not use the in-built function for tidal correction, but post-processed the data using a program which improves on the Longman's algorithm (Nakai, 1979). Residual gravity signals obtained after removal of a linear drift and of an Earth tide model are compared with the measured changes in water level of Te Horu cauldron. Cyclic signals whose amplitude are about 10 microGal are recognized in the low-pass filtered gravity recordings (Figure 5). Water level recordings suggests that our measurements were made during the higher Te Horu water level, therefore during a stable eruption pattern.

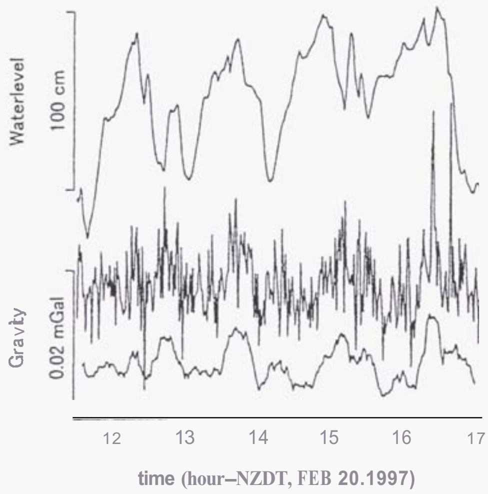

Figure 5- Observed gravity records (unfiltered and low-pass filtered) and Te Horu water levels.

4. INTERPRETATION

4.1 Effect of Water level Changes in Te Horu Pool

At first we evaluated gravity changes induced by water level changes in Te Horu pool. It is estimated to have a cross-section area of about 19 m^2, extending down below its lip by about 5 or 6 meters at least, having been sounded to about 26 meters depth, and so its total volume is perhaps several hundred cubic meters (Weir et al., 1992). The water level varied between 1.5 to 2.8 m below the lip during our measurements. Relative volume change during our measurements, therefore, can be estimated to be the product of relative water level change and the cross section area. We must assume the shape of the cross section of the pool to calculate gravity changes induced by water level changes in the pool. The diameter of the vent seems to be longer in the direction along the Te Puia fault than in the perpendicular direction. We assumed two cases (5 m x 4 m and 6 m x 3 m) for the shape of the cross section. Calculated gravity changes accompanied with water level changes between 1.5 to 2.8 m below the lip are essentially the same for the two models (Figure 6); relative gravity varies nearly proportionally to the relative water level at the rate of 4 microGal/m. This relation was applied to the observed water level changes to calculate the gravity changes induced by the water level changes. This component is smaller than the observed gravity changes (Figure 7).

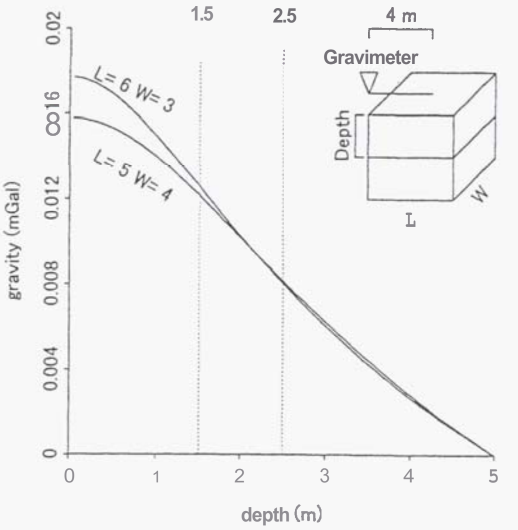

Figure 6- Calculated gravity changes related to Te Horu water level changes.

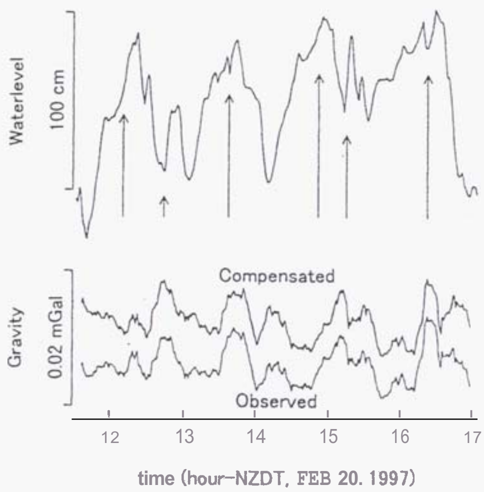

Figure 7- Interpretation of the observed records along the time axis.

4.2 Effect of Reservoirs

What could be the source of the observed gravity signal (10 microGal in amplitude) ? During an eruption, the waters in the reservoir may be merely agitated, partially erupted, or totally emptied (Figure 8), and it is difficult to estimate the capacity of the reservoir. For example the range of apparent density of the reservoir is 0 to 1000 kg/m^3. Can this be the source of the observed gravity changes?

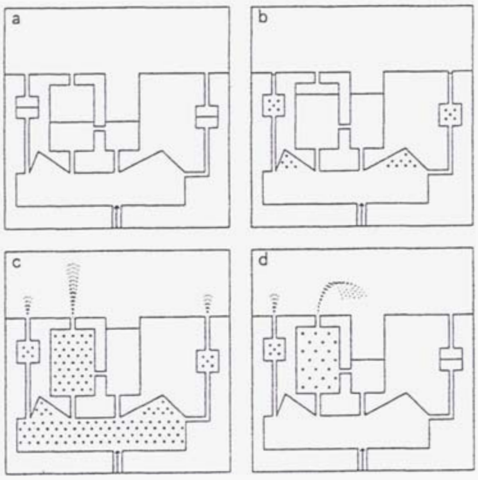

Figure 8- A diagram illustrating the sequence of events in Whakarewarewa Geyser Flat which leads to flash boiling and eruption of a column of water (simplified from Lloyd., 1975).

Assuming the shape and position of the reservoir similar to Figure 8, we calculated gravity changes which accompanied the full-scale changing of apparent density in the reservoir. The results are shown as gravity contours on the coordinate plane (depth and distance from the gravimeter) where a reservoir exists (Figure 9). The shape of the reservoir is assumed to be a cuboid whose sizes are (a) 5 x 5 x 4 m^3 and (b) 20 x 10x 4 m^3. We assume two situations: (a) a shallow reservoir connected to a vent; (b) a deep reservoir connected to the shallow reservoir, following the models developed by Weir et al. (1992; Figure 8). They estimated the volumes of hot water ejected during an average eruption for PWF, Pohutu and Waikorohihi to be 10, 100 and 50 m^3 respectively. These values seemed to be the minimum volume of the reservoirs and guided our assumption of the sizes (a). The sizes (b) are assumed to be as long as the distance between PWF and Waikorohihi vents (width and height are assumed to be equal or larger than those of (a)). A reservoir whose position is on the contour line of 10 microGal could be the source of the observed gravity changes, if all the reservoir fluid is discharged. The reservoir on the contour line of 20 microGal could be the source if the steam fraction is changed from 0 to 50 % in the volume. Considering the result of the calculation (Figure 9) and the sequence of events shown in Figure 8 we would consider case (a) may be more realistic than case (b). A reservoir connecting to Pohutu or Waikorohihi is plausible. The arched recesses of the deep reservoir (Figure 8) which is important in Lloyd's model (Lloyd, 1975) could be the source.

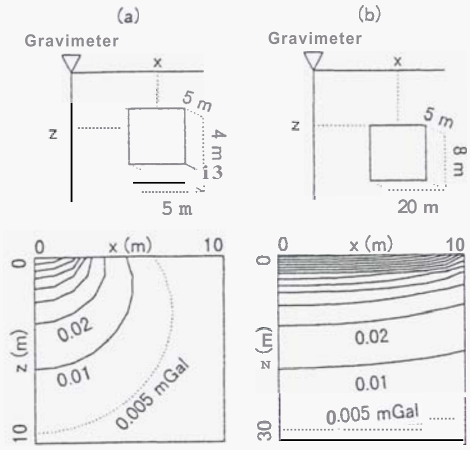

Figure 9- Gravity changes induced by mass changes in an assumed cuboidal reservoir. (a) 5 m in length, 5 m in width, and 4 m in height. (b) 20 m in length, 5 m in width, and 4 m in height.

The next step would be to examine the behavior of the above source with the known sequence of geysering activity (Figure 3, Figure 8). Unfortunately no visual records of geyser activity are available during our measurements. However some information can be inferred from the observed water level changes and relating them to the schematic diagram of regular geyser behavior shown in Figure 3. Four major gravity increases are observed and all appear to occur at the time an eruption begins at Pohutu vent. However, a minor gravity increase is also observed during the cessation period. Also the actual water level changes are not as systematic as those shown in Figure 3. With these data it is not easy to interpret with certainty the relation between the observed gravity changes and the sequence of geysering activity.

4.3. Tilt Response of the Gravimeter

Strictly speaking we cannot assert that the gravity signals shown in Figure 5 were completely compensated. The tide correction procedure which we used does not fully remove all tidal signatures in New Zealand (Sugihara, 1999). However, the tidal component has the longer dominant period than that of the observed gravity signal, and can be ignored in this case.

Another uncertainty is the tilt compensation. The gravimeter should be set within the tilt range of ±10 Arcsec. Figure 10 shows the tilt of the gravity meter went beyond the range, reaching to 30 Arcsec. However, even this degree of tilt may not cause a large problem due to the automatic tilt correction as described the gravimeter manual.

Looking at Figure 10, particular tilt motions are recognized at the time of Pohutu geysering. The particle motion plot shows that the direction of this motion is toward Pohutu vent. It may be that meaningful signals accompanied the geysering activity.

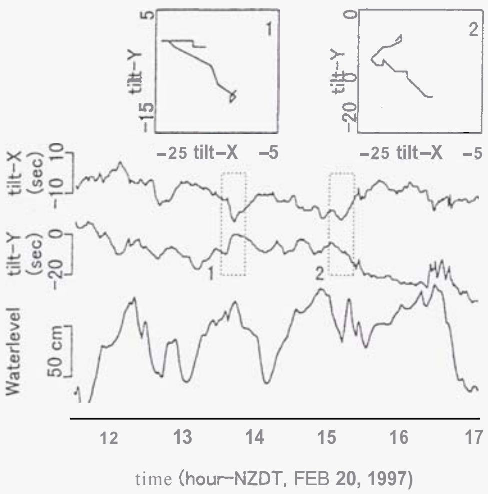

Figure 10- Tilt response of the gravity meter during the measurements at Geyser flat. Particle motion during the two time windows marked by 1,2 are displayed.

5. CONCLUDING REMARKS

These data show it may be difficult to interpret the relation between the observed signals and the dynamic sequence of geysering activity, even if visual records of geyser activity are available. These data also show that the geyser complex of Whakarewarewa Geyser flat seems to be too complicated to interpret from continuous gravity measurements at a single point.

However, these measurements provide preliminary results and a basis for a more elaborate gravimetric survey. We detected signals not only in gravity but also in tilt. Therefore, simultaneous observation using a tiltmeter could be effective. Careful tilt-response calibration is also effective for making use of tilt data recorded in the gravimeter as well as for avoiding tilt correction problems. Continuous measurements using two or more Scintrex gravimeters may be promising; for example, a gravimeter is set at the same point throughout the period, while another gravimeter is set at a point during a cycle of the geyser eruption and then set at another point during the next cycle.

At Whakarewarewa Geyser flat, the cyclic behavior and accessibility make it an ideal natural laboratory for studying gravimetric signals associated with multiphase flow in near-surface hydrothermal features.

ACKNOWLEDGMENTS

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