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CONTINUOUS GRAVITY MEASUREMENTS FOR RESERVOIR MONITORING

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ABSTRACT

In order to improve the accuracy of repeat gravity surveys for reservoir monitoring, it is desirable to perform continuous gravity measurements in addition to the ordinary survey program. We can apply time series analysis to the continuous recording to evaluate the causes of various gravity variations. We have made continuous gravity measurements using a Scintrex CG-3M gravimeter at several geothermal fields and succeeded in evaluating the causes of gravity variations; tidal effects, atmospheric pressure effects, hydrological effects and the others.

INTRODUCTION

Local changes in gravity may occur corresponding to exploitation operations in geothermal fields. Long-term changes which evolve over months and years can be monitored by gravity measurements with profile or areal coverage at respective repetition intervals. Such measurements have been made in geothermal fields in New Zealand (Allis and Hunt, 1986; Hunt and Kissling, 1994). If short-term changes are expected, high repetition rates and/or continuous gravity recordings will be required. Olson and Warburton (1979) have first reported the results of continuous measurement at a geothermal field using a superconducting gravimeter. One-month data segment obtained at The Geysers field indicates that it is possible to accurately observe the steady decrease in gravity associated with continuous steam production and thus provide the most direct available measure of reservoir recharge. Goodkind (1986) also showed correlations between changes in gravity and condensate reinjection rates at The Geysers. A superconducting gravimeter is, however, so expensive that it has been scarcely introduced in practical use.

Spring gravimeters could be used for continuous recording of gravity. LaCoste and Romberg (L & R) models, which are most popular spring gravimeters, have optional functions for continuous recording. However, these are poorly adapted to difficult field conditions such as those encountered in geothermal fields. A new generation spring gravimeter, Scintrex CG-3M gravimeter, which is a microprocessor-based automated gravimeter, has been released in the market. Several recent studies have confirmed the capabilities of the Scintrex models for network reoccupation measurements in geothermal fields (Ehara et al., 1995) and at active volcanoes (Budetta and Carbone, 1997). A cycling mode for continuous automatic recording is also available; Bonvalot et al. (1998) showed a potential impact of the Scintrex models on continuous monitoring of active volcanoes. In this paper we examine potentialities of continuous gravity measurements with CG-3M gravimeters on the studies of reservoir monitoring.

CONTINUOUS MEASUREMENTS AT WHAKAREWAREWA GEYSER FLAT

Geysers activities are unstable processes that transfer water and heat from an underground reservoir to the earth's surface (e. g. Reinhart, 1980). Figure 1 is a conceptual model of the geysers in the Whakarewarewa geothermal area, New Zealand. In order to investigate the geyser activity, we carried out continuous gravity measurements at Whakarewarewa on 20 February 1997 (Sugihara et al., 1998). We acquired 52 mean values of the 60 seconds sampling using a Sintrex CG-3M gravimeter (serial #270). The gravimeter was set inside a plastic container to protect it from geyser spray, at a place nearby Te Horu pool that is next to the largest geyser Pohutu. Water level changes were also measured in Te Horu pool.

Figure 2 shows the observed gravity changes. We have compared them with gravity changes calculated from the measured changes in water level. The matching between the observed and calculated gravity changes is not good, which suggests that the observed gravity changes are mainly brought about by changes in water level and steam distribution within the underground reservoir .

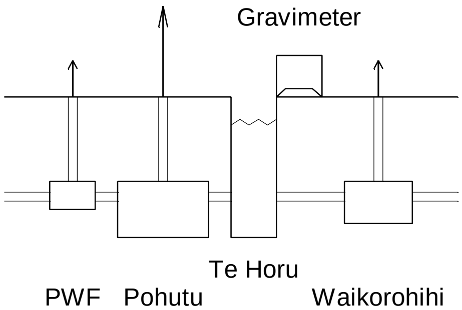

Figure 1. A schematic model of Whakarewarewa Geyser Flat, New Zealand. Three geysers (PWF, Pohutu and Waikorohihi) are active and the water level in Te Horu pool changes.

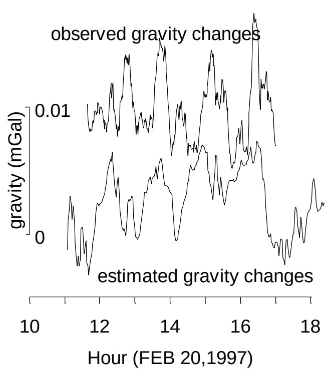

Figure 2. The gravity changes estimated from the changes in water level in Te Horu pool (lower line) and the observed gravity changes (upper line). The observed gravity changes was low-pass filtered.

CONTINUOUS MEASUREMENTS AT WAIRAKEI

In 1996 we made gravity measurements at a few hundreds points in the Taupo Volcanic Zone, New Zealand. Before the measurements we set a CG-3M (serial #270) for eleven days to check the drift rate at a reference point in the X-ray laboratory in Building 3, Wairakei Research Center. The gravimeter was set to record values averaged over two minutes, every ten minutes.

Large offsets caused by moderate Kermadec earthquakes are seen in the record (Figure 3). A change with a longer period appears as the residual earth tide components. CG-3M has an in-built function to correct for the earth-tide effect using the formulae given by Longman (1959) assuming the amplification factor to be 1.16 and the lag time as zero. We did not use the in-built function for tidal correction, but followed usual procedure at Wairakei, that is, assuming the amplification factor to be 1.20 (Hunt, 1988). Figure 3 suggests that the tide correction procedure does not fully remove all tidal signatures.

Another tide correction using the program GOTIC (Sato and Hanada, 1984) were made. The GOTIC program calculates amplitudes and phases of the oceanic gravity tides for major 9 components by using the Schwiderski's oceanic tidal model and the Green's function based on the 1066A Earth model. The secondary effect of elastic deformation of the earth to tidal loading was thus appropriately considered. The result has substantially improved, but still contains semi-diurnal components. This is partly because the amplitude and phase of the semi-diurnal component of the oceanic tide depend largely on the location and the results are influenced by the accuracy of topographical maps of the program.

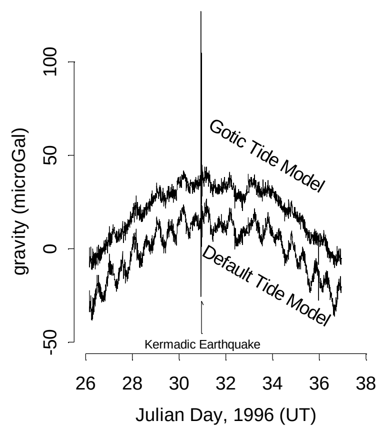

Figure 3. A 11-day data segment from Wairakei. Residual signals obtained after removal of a linear drift and two tide models.

TIME SERIES ANALYSIS

Time-series data acquired from continuous gravity measurements contain information about tide, instrumental effects, influences of external mass displacements (atmospheric, hydrological, and tectonic processes), and measurement errors. The program BAYTAP-G can be adapted to data which include tidal effects and irregularities such as drift, occasional steps and disturbances caused by meteorological influences (Tamura et al., 1991). Figure 4 is a flow chart of BAYTAP-G. The basic assumption of the method is the smoothness of the drift. This assumption is represented in the form of prior probability in the Baysian model. Once the prior distribution is determined, the parameters used in the analysis model are obtained by maximizing the posterior distribution of the parameters. In contrast to the previous methods, only the smoothness of the drift is assumed in this new procedure. In order to determine the precise cause of various variations, it is first necessary to look for a possible correlation between the gravity observations and other parameters simultaneously recorded (e.g. atmospheric pressure, groundwater level, rainfall). If a correlation with environmental variables is found, it can be studied for phenomena of interest or used to eliminate uninteresting effects. (It seems interesting to apply the program BAYTAP-G to the data shown in Figure 3. However, only eleven days of data are not enough to separate the main tidal components.)

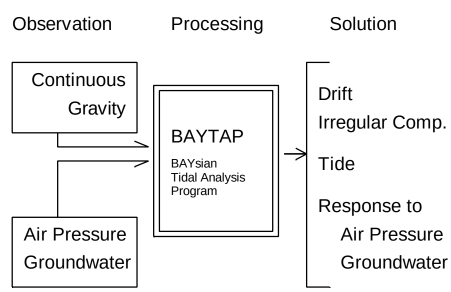

Figure 4. A flow chgart of the program BAYTAP-G.

We tried to apply the method to data from the Sumikawa geothermal field in northern Japan. Since 1994, we have been carrying out repeat microgravity surveys using a LaCoste & Romberg D gravimeter (serial #35) at Sumikawa. Gravity changes corresponding to fluid reinjection have been observed since full-scale plant operation began in 1995. The observed microgravity changes were in good agreement with earlier predictions based upon a mathematical reservoir model (Sugihara and Ishido, 1998). The accuracy of the measurements were evaluated to be 10-20 microGal.

In order to perform reproducible measurements, it is important for us to evaluate tide and other effects on gravity measurements. We, therefore, made continuous gravity measurements using a CG-3M (serial #352) at Sumikawa in 1997. Recordings were made at a sampling rate of one point per 10 minute (cycle time 600 seconds, read time 120 seconds). To ease the reading of the time-series recording over a long period of time and to facilitate their comparison with other recordings made simultaneously (atmospheric pressure, rainfall, and groundwater level), the gravity signals were later re-sampled at a sampling rate of one point per an hour. Figure 5 shows the raw gravity recordings acquired with a Scintrex CG-3M gravimeter. The drift parameter was set to zero in order to quantify the actual instrumental drift. Residual gravity signals obtained after removal of a quadratic drift are shown in Figure 6.

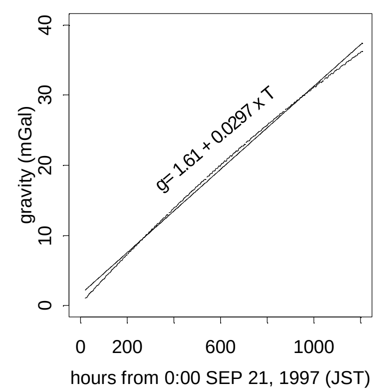

Figure 5. The raw gravity recordings at Sumikawa.

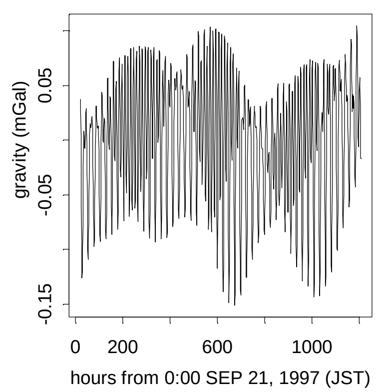

Figure 6. Residual gravity signals obtained after removal of a quadratic drift.

It is seen that the quadratic model correctly fits the instrumental drift for the gravimeter. Amplitude factors and phase delays of twelve tide constituents were determined. A coefficient of gravity changes corresponding to groundwater level changes at the site was estimated by BAYTAP-G as 2.0 microGal / m. Assuming horizontally structure we can estimate from this value porosity to be 5 percent.

Figure 7 shows the result of another field. Recordings were made at a sampling rate of one point per minute at the Amihari Absolute Gravity Station, about 6 km to the east of the Kakkonda Geothermal Power Plant (Sugihara and Yamamoto, 1998). Tide effects and atmospheric pressure effects were decomposed by BAYTAP-G. The drift components for two models are shown in Figure 7. Model 1 includes the response to air pressure, Model 2 does not. Model 0 includes the difference of tidal components to the Longman's model.

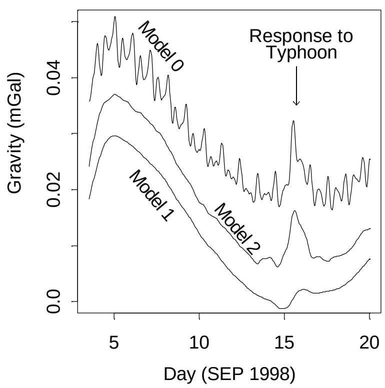

Figure 7. The results of decomposition by BAYTAP-G. The drift components for two models are shown. Model 1 includes the response to air pressure, Model 2 does not. Model 0 includes the difference of tidal components to the Longman's model.

DISCUSSION

Analysis of measured gravity changes allows us to evaluate values of reservoir properties such as permeability or storativity. Now consider the two cases which Hunt and Kissling (1994) examined. One case is for the early stages of exploitation when a two-phase zone is rapidly expanding. The second case is for the effects of reinjection into a deep-liquid zone overlain by a two-phase zone. The peak anomaly was 415 microGal and 120 microGal for the first and second cases, respectively. The accuracy obtained by reoccupying the networks with spring gravimeters (L&R, CG-3M) usually varies from 10 to 20 microGal (Hunt, 1988; Torge, 1989). In order to infer reservoir properties from gravity change data, it is important to reduce uncertainties as small as possible. Harnisch (1993) discussed systematic errors which influence the accuracy of high precision gravity measurements: tidal effects, atmospheric pressure fluctuations, hydrological effects and local gravity variations. The first three effects can be separated by continuous gravity monitoring. Tidal and atmospheric effects change in time, but are almost uniform in space on a small network such as used for the geothermal reservoir monitoring. Therefore, it is effective to make continuous measurement at a point in the study area. It may be useful even if a period of the continuous measurement is a few months or less. Usually amplitude and phase of each tidal component do not change so much. It is the same with admittance of atmospheric pressure (see van Dam and Francis, 1998).

At present the greatest uncertainties arise from hydrological influences. Harnisch (1993) estimated that gravity variations are more than 10 microGal and more than 30 microGal for the soil moisture and the groundwater influences, respectively. Generally speaking these hydrological effects appear in microgravity recordings differently at each station in a geologically heterogeneous area such as geothermal fields in Japan. Hunt and Kissling (1994) proposed plans of gravity monitoring for the two cases mentioned above: gravity monitoring at a few selected points in the borefield area for several years at a 6-12-month interval, gravity monitoring at a few selected points around the injection well for several years at about three-month intervals. Continuous recordings at the selected points during the intervals are significant to evaluate the systematic errors. Continuous recording may be useful to select a few stations which are appropriate for the reiteration network and not sensitive to shallow hydrological effects.

It is efficient for improving the signal-to-noise ratio to low-pass filter the data recorded at a high sampling rate. Sugihara and Tamura (1998) made a continuous gravity measurement at the Esashi Earth Tide Station of the National Astronomical Observatory (latitude 39-08-53 N, longitude 141-20-07 E), where a superconducting gravimeter are operating. Recordings were made at a sampling rate of one point per one minute (cycle time 60 seconds, read time 48 seconds) and data were transferred to a personal computer through the RS-232C port. The separated tidal components of the CG-3M data were in agreement (within 0.5 microGal) with those from the superconducting gravimeter. Considering the nominal accuracy of the CG-3M is 1 microGal, it is quite a marvelous fact. In addition to that the ground noise level is quite low and the ambient temperature is well controlled at the site, digital filtering was quite effective to get this good result.

CONCLUDING REMARKS

Although the data presented here are insufficient to yield new conclusions concerning reservoir processes, they do demonstrate that continuous gravity recording with CG-3M meters is a promising tool for geothermal reservoir monitoring. Continuous microgravity recordings associated with conventional reiteration networks will probably improve the accuracy of reservoir monitoring.

The accuracy obtained by reoccupying the networks with spring gravimeters (e.g. L&R, CG-3M) usually varies from 10 to 20 microGals. Comparing this accuracy to observable signals we have not enough resolution to analyze reservoir properties. It is efficient for improving the resolution to make continuous gravity recording for a month or two at a few selected stations in and around the network. It is useful, especially in Japan because several CG-3M meters have already introduced for reservoir monitoring (Ehara et al., 1995; Nakanishi et al., 1998), and reducible systematic errors are likely to be contained in microgravity observations. We have many sources of the systematic errors which influence the accuracy of high precision gravity measurements in Japan: (1) oceanic tide effects are large, (2) low atmospheric pressure area moves across the Japanese islands frequently, and (3) heavy rainfall may cause significant hydrological effects. To reduce the systematic errors and evaluate reservoir parameters more precisely, it is desirable to make use of (the existing) CG-3M meters not only for reiteration surveys but also for continuous measurements.

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