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CONTINUOUS GRAVITY MEASUREMENT FOR PRACTICAL MONITORING

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ABSTRACT

Examining the possibility of sequestering CO2 gas in shallow aquifers continuous gravity measurement is promising tool for monitoring. The calculated microgravity disturbance is expected to be smaller at the earth surface for the deeper cases, however, can be detectable using a superconducting gravimeter. A new superconducting gravimeter model has been simplified for portable and field operation, but retains the stability and precision of previous superconducting gravimeters. We try to apply it for continuous gravity monitoring at a CO2 sequestration site. A new type of metal spring sensor gravity meter is another choice. It also has a large dynamic range and enough sensitivity to record the continuous background seismic and earth tide activity. We made preliminary continuous recording with the gravimeter at a geothermal field and confirmed the performance of the gravimeters and detected particular signals.

INTRODUCTION

Sugihara (1999) made continuous measurements with Scintrex CG-3M gravimeters at several geothermal fields and succeeded in evaluating the causes of gravity variations; tidal effects, atmospheric pressure effects, hydrological effects and the others. It was concluded that continuous microgravity recordings associated with conventional reiteration networks will improve the accuracy of reservoir monitoring.

For local high-precision monitoring of gravity changes, as in the case of geothermal reservoir, a high-performance absolute reference and station monitoring is required. For local monitoring network observations, high-performance relative portable gravimeters are adequate. Absolute measurements with an FG5 gravimeter provide a reliable reference datum for relative spatial surveys. As a result of these hybrid measurements, Sugihara and Ishido (2008) succeeded in delineating the distribution of not only long-term changes for four years but also short-term changes induced by the fieldwide shut-in of production and reinjection wells in the Ogiri geothermal field. Adding a new generation of superconducting gravimeter to the hybrid system Sugihara and Ishido (2010) proposed the super-hybrid gravity monitoring method. Now we are applying the method in two fields; (1) a CO2 geo-sequestration test field in Utah, (2) a geothermal field in Japan. In this paper we will show the two programs. First, however, continuous gravity changes at a simple model will be examined.

A SIMPLE CASE OF CO2 SEQUESTRATION IN SHALLOW AQUIFERS

Numerical models of geothermal reservoirs are never precise, owing to the problem of non-uniqueness. A technology to utilize geophysical monitoring data as well as well data was developed to reduce the inherent non-uniqueness of any mathematical reservoir models (Ishido et al., 2005). The technology is based on a computer program, so called geophysical postprocessor, which calculates changes in observables such as gravity, self-potential (SP), etc. from changing underground condition computed by reservoir simulations (Figure 1).

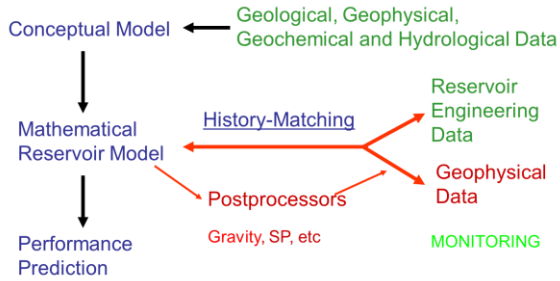

Figure 1: Geothermal reservoir modeling. Various computational postprocessors permit the user to calculate temporal changes that are likely to be observed if geophysical surveys of an operating geothermal field are repeated from time to time. Results may be used to supplement conventional reservoir engineering measurements in history-matching studies undertaken during geothermal reservoir model development (Ishido et al., 2005).

To appraise the utility the scheme shown in Figure 1 for monitoring CO2 injected into aquifers, Sugihara and Ishido (2009) carried out numerical simulations of an axisymmetric aquifer system, that is, a vertical injection well in a homogeneous permeable aquifer confined between impermeable aquitards above and below. The study used the STAR general-purpose reservoir simulator with the SQSCO2 equation-of-state package which treats three fluid phases (liquid- and gaseous-phase CO2 and an aqueous liquid phase) to calculate the evolution of reservoir conditions, and then used postprocessor to calculate the resultant temporal changes in the earth-surface distribution of microgravity.

These calculations of gravity change suggest that microgravity monitoring can be an effective technique for characterizing the subsurface flow of CO2 injected into underground aquifers. The signal strengths calculated here are not particularly large, but should be detectable using a high-precision continuous gravity measurement technique.

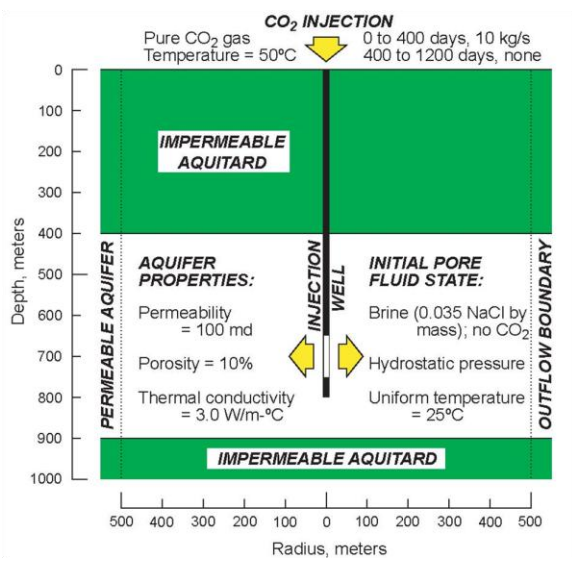

Figure 2: Problem geometry. A uniform homogeneous isotropic horizontal permeable aquifer extends from 400 to 900m depth. A vertical injection well pumps CO2 into the aquifer starting at t=0 a constant rate of 10 kg/s. Injection ceases after 400 days. The axisymmetric region considered for the calculation extends from 0 to 500 m radius, and from 400 to 900 m depth. Fixed pressure outflow conditions are imposed at the outer boundary. Initial conditions are hydrostatic, and the temperature and fluid salinity in the aquifer are both initially uniform. In the Base Case, the native aquifer fluid consists of a dilute saline brine (NaCl mass fraction = So= 0.035).

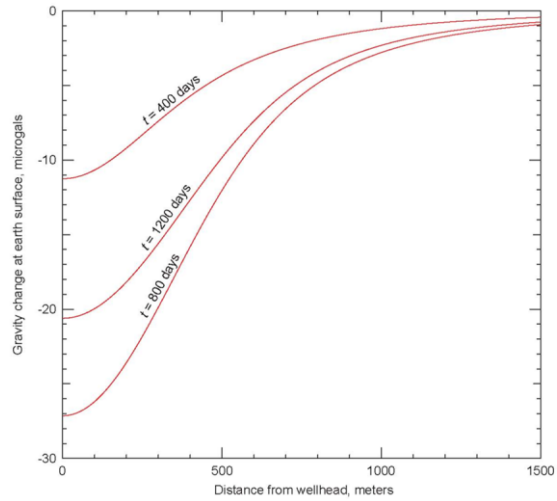

Figure 3a: Base Case: earth-surface change in gravity after t= 400, 800 and 1200 days as a function of distance from the wellhead.

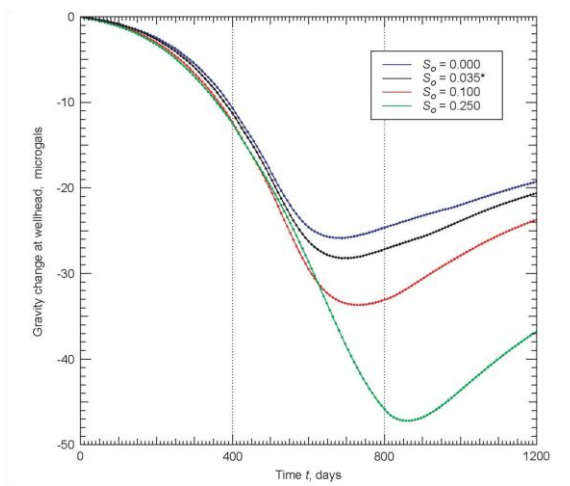

Figure 3b: Influence of aquifer salinity (So) upon the change in earth-surface gravity as measured at the wellhead as a function of time. CO2 injection ceases at t= 400 days. Blue: salinity= 0, black=0.035, Red: salinity= 0.1, Green: salinity= 0.25.

Olson and Warburton (1979) have first reported the results of continuous measurement at a geothermal field using a SG meter. 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 SG meter is, however, so expensive not only to purchase but also to maintenance that it has been scarcely introduced in practical use. The iGrav is a new SG model that has been simplified for portable and field

operation, but retains the stability and precision of previous SGs. with a drift rate of less than 0.5 microGal/month and a virtually constant scale factor. It will be used to record continuous gravity variations and track water mass variations at a few millimeters level. It is high time to introduce a new type SG meter for practical use.

A TRIAL OF SUPER-HYBRID GRAVITY MEASUREMENT FOR CO2 SEQUESTRATION MONITORING

We are applying the super-hybrid gravity monitoring at a CO2 sequestration field in Utah along with US's project of Southwest Regional Partnership. One of the purposes of our study is development of monitoring method for both lower cost and enough high safety in CO2 geo-sequestration by complementing standard seismic survey with various other geophysical techniques, especially gravity monitoring. Our basic concept has consideration for Japanese specific situation for CO2 geo-sequestration (Soma et al., 2011). We have started gravity measurement at the field. A couple of pillars were made at the test site for parallel measurement with an absolute gravimeter and a superconducting gravimeter (Figure 4). The first absolute gravity measurements were made using an A10 absolute gravimeter in December 2011.

Figure 4: A base station is under construction at a CO2 sequestration test site in Utah. A couple of piers are made for parallel measurement with an absolute gravimeter and a superconducting gravimeter.

A TRIAL OF SUPER-HYBRID GRAVITY MEASUREMENTS FOR GEOTHERMAL RESERVOIR MONITORING

Understandings and agreements of local residents are essential for new geothermal exploitations. However, in some cases, geothermal projects have been delayed or stopped due to the concerns of local hot spring owners that their springs would be interfered or ruined by geothermal exploitation. Thus in Japan, it is quite difficult to exploit geothermal energy without cooperation with hot spring operators. In order to solve the problem, a three-year research project has been begun since fiscal year 2010 (FY2010). The purposes of the project are to develop an integrated geothermal reservoir operation system for adequately controlled utilization and to prove that geothermal exploitations can be performed without interfering to nearby hot springs (Yasukawa et al., 2011).

The final goal is to develop a reliable monitoring system that can detect small effects on a hot spring caused by geothermal exploitation. We aim to detect a change in groundwater and hot spring water level with a resolution of 10 cm. Roughly it is equivalent to a resolution of 1 microGal by a continuous gravity monitoring (Figure 5). At first we intended to introduce a superconducting gravimeter into the project. The budget, however, was restricted to use for rental equipment. We introduced a new type of metal spring sensor gravity meter gPhone gravimeter instead of a superconducting gravimeter. In 2010FY we used three gPhone's at the geothermal field for two months. Another gPhone was used for parallel measurement with a superconducting gravimeter at Matsushiro observatory for two months to compare the performance of the two gravimeters. In 2011FY continuous monitoring is going on using a gPhone gravimeter.

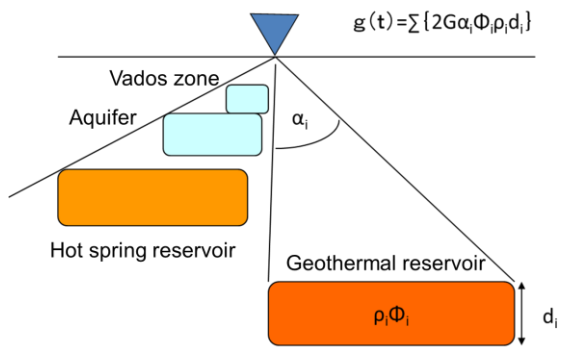

Figure 5: A schematic diagram of sources of gravity changes at the Hachijojima geothermal field.

Hachijojima island, a gourd-shaped volcanic island in the Pacific Ocean, is located 300 km south of Tokyo. In the southern area a 3.3 MWe geothermal power station has been in continuous operation since March, 1999 and several hot spring wells were drilled (Matsuyama et al., 2000). Ring structures occur in the area and parasitic volcanoes exist on top of these structures. These fractures channel the upflow of geothermal fluid. A low-permeability cap rock prevents the penetration of seawater and ground water into the geothermal system (Figure 6). A monitor well was drilled for the project between the power station and a hot spring.

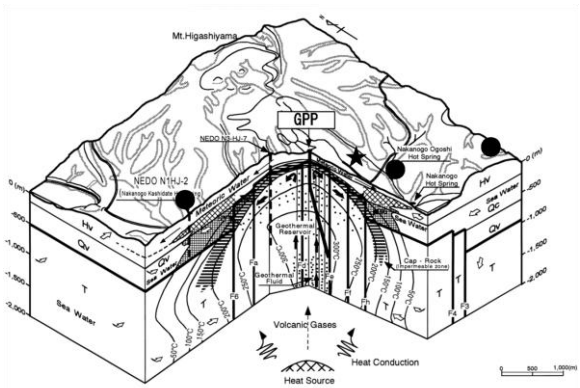

Figure 6: Location of the project site and the geothermal model of the southern area (modified from Matsuyama et al., 2000). Water level and temperature are monitored at three hot springs (solid circles). A star indicates the new monitor well.

We made a side-by-side test with two gPhone gravimeters at the new monitor well site. Figure 7 indicates not only the effect of the initial drift of gPhone109 but also common features between the two meters. Overnight continuous measurement with the CG5 gravimeter was made several times at a hot spring site. We detected a particular signal not in gravity but in tilt associated with water level variations (Sugihara et al., 2011).

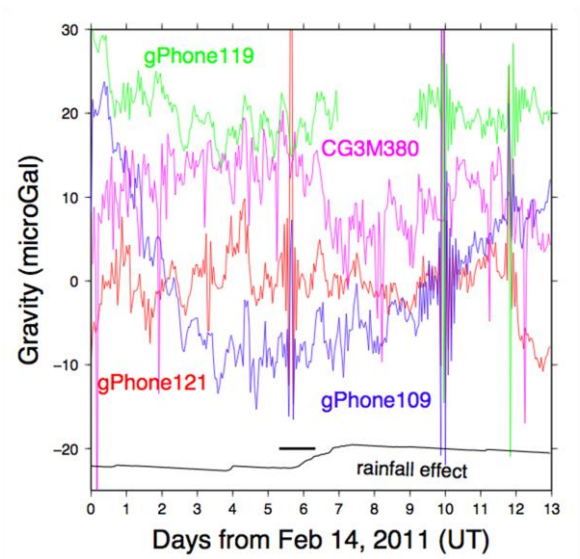

Figure 7: Thiteen days continuous record with three gPhone gravimeters and a CG3M gravimeter.

DISCUSSION

A microprocessor-based automated gravimeter, Scintrex CG3M can be operated in cycling mode, when data acquisition is triggered at a pre-defined sampling rate (10 points per minute or lower). The CG5 meter has a new capability of raw data acquisition, which enables us to store the unprocessed 6 Hz data (gravity, tilt-x, tilt-y, and internal temperature) in memory. We made continuous gravity measurements using CG3M/CG5 gravimeters at several geysers (Table 1).

Table 1: Continuous measurements have been made using CG3M/CG5 gravimeters at five geysers.

Name of Geyser	state	Gravimeter	reference
Pohutu and Others	NZ	CG3M	Sugihara et al.(1999)
Lady Knox (controlled)	NZ	CG3M & CG3M	Sugihara et al.(2004)
Waikite (dormant)	NZ	CG3M	Sugihara et al.(2003)
Hirogawara (CO2)	JPN	CG5 & CG3M	Sugihara (2010)
Crystal Geyser(CO2)	USA	CG5	Sugihara & Soma (2012)

We detected a particular signal not in gravity but in tilt. Geyser activities are unstable processes that transfer water and heat from an underground reservoir to the Earth's surface. Continuous gravity record at each site constrains the volume and/or the depth of the reservoir which is supposed to supply fluid for each geyser activity. This result is of particular interest in field surveys of temporal gravity changes related to some environmental or geodynamical processes, where gravity variations are expected to occur in hours or shorter period. However, the range of the timescale is too narrow to apply it for practical monitoring.

Temporal gravity changes, in which many scientists have been interested, are divided into two categories of earth tides and related global phenomena on the one hand, and temporal variations caused by local terrestrial mass displacements on the other. Gravity changes caused by groundwater variations can be a target in the latter category, and have often been detected as a major noise source in the former. Most of superconducting gravimeters have been installed for the former and revealed groundwater effect. We have ever been detected it (Nawa et al., 2008, 2009). Figure 8 indicates not only the detected signals but also the difference between superconducting gravimeter and CG3M gravimeter. We have interest in how is the performance of gPhone gravimeter. We will evaluate and improve it in the Hachijojima project.

Uncertainty for time-lapse hybrid measurements is larger than instrumental accuracy for FG5. At the Ogiri field fluctuations in survey values are thought

to be +-5 microGal, which might be caused by changes in shallow hydrologic conditions (Sugihara and Ishido, 2008). Such uncertainty can be detected using continuous measurements. Particular gravity changes accompanied with particular hydrological variation were detected by particular measurement. A combination of the above continuous measurements and reiteration surveys can cover a considerable part of the ranges both in time and space.

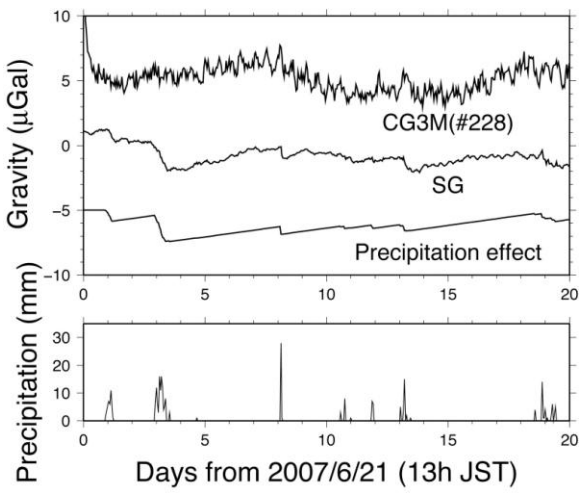

Figure 8: Comparison between observed gravity changes and estimated precipitation effect at the period June to July 2007. Precipitation, used for the input to the tank model, in this period also plotted at the bottom. Gravity changes were observed using a superconducting gravimeter (SG) and a CG3M meter (Nawa et al., 2008).

CONCLUSIONS

Although the data presented here are insufficient to yield new conclusions, they do demonstrate that continuous gravity recording with superconducting gravimeters or gPhone gravimeters is a promising tool for practical monitoring. Continuous microgravity recordings associated with conventional reiteration networks will probably improve the accuracy of monitoring. Improving the accuracy of observable signals we have enough resolution to analyze reservoir properties. It is efficient for improving the resolution to make continuous gravity recording for proper period at a few selected stations in and around the network.

The initial cost of the super hybrid system is still high, however, the benefit can be reasonable to the cost. The scenario is as follows: (1) prospective fields are chosen by simulation calculation, (2) super hybrid measurements are made at the field, (SG meter works continuously and time-lapse hybrid measurements are made at the period), (3) the super hybrid system moves to the next potential field, (4) observed data would appear to constitute useful constraints for future history-matching studies based on revised models.

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REFERENCES

Goodkind, J. M., Continuous Measurement of nontidal variations of gravity, J. Geophys. Res., 91, (1986), 9125-9134.

Ishido, T., Goko, K. Adachi, M. Ishizaki, J. Tosha, T. Nishi, Y. Sugihara, M. Takakura, S. and Kikuchi, T. (2005), System integration of various geophysical measurements for reservoir monitoring: World Geothermal Congress 2005, Proceedings, paper number 1160.

Ishido, T., Nishi, Y., Sugihara, M., Temma, N. and Tosha, T. (2008) Changes in Geophysical Observables Caused by Carbon Dioxide Injection Into Saline Aquifers, *Abstract AGU fall meeting*, H23D-0993.

Matsuyama, K., Narita, N., Tomita, K., and Majima, T., 2000, Geothermal resources of Hachijojima, *Geothermics*, **29**, 213-232.

Nawa, K., Suda, N., Yamada,. I., Miyajima, R. and Okubo, S. (2009) Coseismic change and precipitation effect in temporal gravity variation at Inuyama, Japan: a case of 2004 off the Kii peninsula earthquakes observed with a superconducting gravimeter, *J. Geodynamics*, 48, 1-5.

Nawa, K., Sugihara, M., Murata, Y., Kazama, T., Nishida, K., Sugano, T., Koyama, E., Okubo, S. and Okuda, T. (2008) Observation of hydrological effects on gravity by using a Scintrex CG-3M gravimeter: a case of typhoon 200709 (FITOW) at Asama volcano observatory, *J. Geod. Soc. Japan*, 54, 59-67

Nawa, K., Sugihara, M., Yamada, I., Okuda, T. and Tanaka, T. (2008) Comparative observation of CG3 (#228, #367, #380, #383) and SG at Inuyama, Aichi, Japan, *Abstract, 108th meeting, the Geodetic Society of Japan,* (2007)

Olson, J. J. and Warburton, R. J., Continuous gravity observations at The Geysers: a preliminary report, *GRC Transactions*, 3, (1979), 519-522.

Soma, N., Nishi, Y., Sugihara, M., Ishido, T., Fijii, T., Nawa, K. and Nakao, S. (2011) AIST's

research activity for Multi-geophysical monitoring at the Gordon Creek test site, Utah, USA, *The 4th AIST-KIGAM joint workshop on CO2 geological storage, Abstracts*

Sugihara, M. (1999) Continuous gravity measurements for reservoir monitoring, *Proc. 24th Stanford Workshop on geothermal reservoir engineering*, 287-292.

Sugihara, M. (2010) An evaluation of the Scintrex CG5 gravimeter; a field trial at the Hirogawara CO2 geyser, *J. Geothermal Research Soc. Japan*, 32, 21-30.

Sugihara, M. and Ishido, T. (2008), Geothermal reservoir monitoring with a combination of absolute and relative gravimetry, *GEOPHYSICS*, 73, no6, WA37-WA47.

Sugihara, M. and Ishido, T. (2009) A feasibility study of gravimetric methods for monitoring geologic CO2 sequestration into aquifers, *Abstracts*

Sugihara, M. and Ishido, T. (2010) Potentiality of the super hybrid gravity measurements for geothermal reservoir monitoring, *Proc. RE2010*.

Sugihara, M., Nishi, Y. and Scott, B.J. (1999) Continuous gravity measurements at Whakarewarewa Geyser Flat, *Proc. 21st New Zealand Geothermal Workshop*, 169-173.

Sugihara, M., Nishi, Y. and Scott, B.J. (2004) Continuous Gravity Recording with Scintrex CG3M/CG5 Meters for Monitoring Geysers, *Abst. 26th New Zealand Geothermal Workshop*., p38.

Sugihara, M., Nishi, Y., Scott, B.J. and Sherburn, S., 2003, Continuous measurements with a Scintrex gravimeter for reservoir monitoring, *Proc. 9th European meeting of Environmental and engineering geophysics*, P025-1-4.

Yasukawa, K., Sakaguchi, K., Tosha, T., Uchida, T., Sasaki, M., Ishido, T., Sugihara, M., Matsuyama, K., Noda, T., Yano, Y. and Matsubayashi, O. (2011) Development of an advanced geothermal reservoir management system for the harmonious utilization with hot spring resources, *Proc. 9th Asian Geothermal Symposium*