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Self-Potential Monitoring with Reservoir Simulation in a Geothermal Field, Japan

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ABSTRACT

To assist in geothermal reservoir management, it is very useful to predict changes in geophysical observables from changing reservoir conditions computed by numerical simulation. We have constructed a three-dimensional reservoir model based upon various data from a geothermal field in Japan. Self-potential (SP) change has been calculated based on the reservoir model which was calibrated against long-term gravity monitoring data.

The calculated SP variation is qualitatively consistent both with a relatively long-term change obtained by repeated surveys and a short-term change detected by continuous measurements, which was associated with a field-wide shut-in of production and reinjection wells for maintenance of the power station.

1. INTRODUCTION

Decline of the geothermal steam production is one of the most serious problems to be solved for the geothermal industry. There are various causes for the decline, such as reservoir pressure and/or temperature drop, change in steam to liquid ratio of produced fluid, scaling and so on. To cope with these problems, numerical reservoir simulation is a key technology for reservoir management. However, a beneficial reservoir simulation needs a proper reservoir model which is well calibrated against various sets of field data. In order to calibrate the reservoir model, temperature and/or pressure data from observation wells are often used However, the observation wells are often located too sparsely to give representative data, i.e. data that will allow proper characterization of the field.

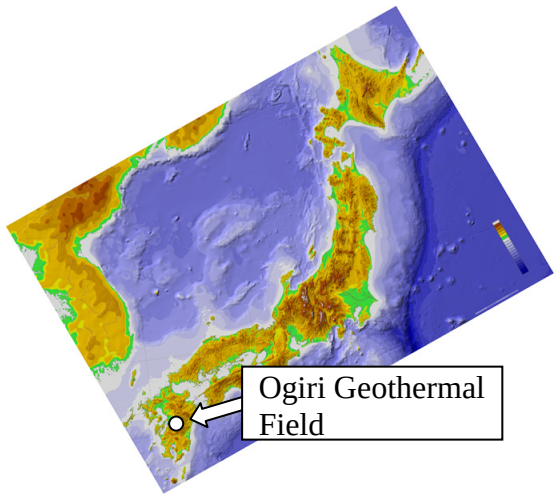

Figure 1: Location of the Ogiri geothermal field

A technology to utilize geophysical monitoring data as well as data from production, injection and observation wells was developed to reduce the inherent non-uniqueness of any mathematical reservoir models (e.g., Ishido et al., 2005). The technology is based on a computer program, a so called geophysical postprocessor, which calculates changes in geophysical observables such as gravity, self-potential (SP), etc. from changing subsurface conditions computed by reservoir simulations.

In this paper we will show the computed SP variation, which is based upon a numerical reservoir model, in the Ogiri field, a geothermal field in Japan. We will discuss a possible way to detect the reservoir change precisely. Part of the results was presented by Tosha et al. (2008).

2. OGIRI GEOTHERMAL FIELD

2.1 Geothermal Power Plant

The Ogiri geothermal field is located in South Kyushu, Japan (in an inset of Figure 1) and a geothermal power plant has been in operation with an installed capacity of 30 MWe since 1996. The main production wells are located in the middle of the field around the power plant; there are 12 production wells with two reserve wells located around the centre of the field. Six injection wells in the western area of the field are in operation and reinject all waste water (Figure 2). The depth of the production and injection wells ranges 987 to 1,992 m and 808 to 1,598 m, respectively. An average production rate is 248 t/h of steam and 745 t/h of hot water in 2007. The all separated brine with a small amount of steam condensate is reinjected (Therm. Nuclear Power Eng. Soc., 2007).

2.2 Geological Setting

Kirishima volcanic zone, on the western slope of which the Ogiri geothermal field is located, is caused by the subduction of the Philippines' sea plate into the Eurasia plate. Fault systems and lineaments are dominant with trends of NW-SE and ENE-WSW. Hot springs, fumaroles, and geothermally altered zones are aligned along this direction, especially along the ENE-WSW oriented faults named as Sakkogawa, Ginyu and Shiramizugoe (from north to south). The subsurface temperature decreases from southeast to northwest and drops steeply beyond the Sakkogawa fault (Goko, 2004). Ginyu as well as Shiramizugoe are, therefore, the major target faults for geothermal development. The basement of the Ogiri field is the Cretaceous-Paleogene Shimanto group found in a boring core below about 1300 m in depth. A geothermal reservoir developed in the Pleistocene formations below about 500 m in depth. Cap rocks consist of altered and crystallised minerals such as smectite are formed at depths between 200 and 500m (Goko, 2004).

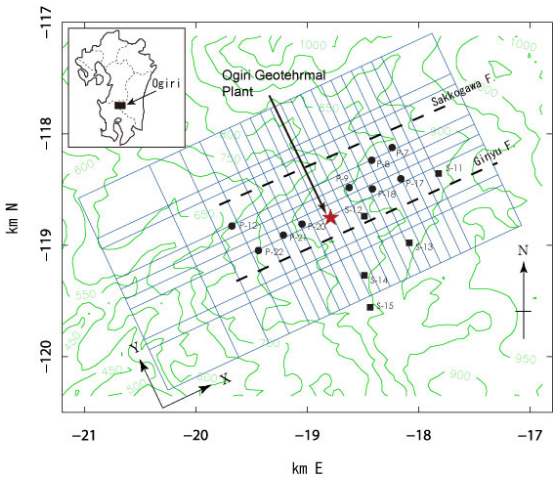

Figure 2: Simulation area and locations of SP electrodes. Closed circles and squares show the locations of SP electrode in shallower (ca.1 m) and deeper (ca.8 m) holes, respectively. Surface traces of two major faults (Ginyu and Sakkogawa faults) are shown by broken lines. Also shown is the computational grid used for the reservoir simulation

3. GEOPHYSICAL MONITORING

3.1 Microgravity Monitoring

Microgravity observations were repeated between 2002 and 2007 at Ogiri, (Sugihara and Ishido, 2008). The absolute gravity measurements were carried out at the centre of the field (S-12 shown in Figure 2) and provided reliable and local reference data for more widely-distributed relative gravity measurements. In the Ogiri field, the time-lapse hybrid measurements with a combination of absolute and relative gravimeters were carried out and the spatial distributions of both long- and short-term changes were obtained.

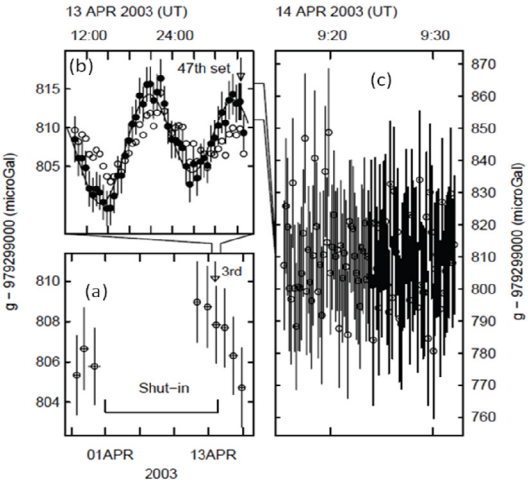

Figure 3: (a)Absolute gravity surveys at the Ogiri field. Two "surveys" were made; the first and second surveys consist of three and six "projects" respectively. (b) The 3rd project of the 2nd survey consists of 48 "sets"), and (c) the 47th set of the 3rd project consists of 100 "drops". In figure (b), the absolute gravity values after correcting for earth tides, polar motion, barometric pressure and vertical gradients are shown. Note that very small change of the absolute gravity (less than 10 micro gal) was observed during the shut-in of the production wells during the annual maintenance in 2003. (after Sugihara and Ishido, 2008)

The default settings of the absolute gravity measurements are to start a series of measurements (a "project") and collect 48 "sets" of 100 "drops" each (the drop interval is 10 seconds and a set of 100 drops is conducted every 30 minutes). Figure 3 illustrates the relations among "drop", "set", "project" and "survey". In this example, the second "survey", which was carried out in April 2003, consists of six "projects" and the third "project" consists of 48 "sets.

The hybrid measurements carried out for more than six years revealed the delineation of spatial distribution of relatively small gravity change. Since the long-term gravity change between 2002 and 2007 was small, a mass balance between the net production rate and fluid recharge rate from the reservoir boundary is thought to be almost established for the period between six and eleven years of fluid production. The previous reservoir model (Yano and Ishido, 1995) was modified and updated so as to reproduce the observed gravity change using the gravity postprocessor. They also applied the same technique during the field-wide shut-in of production and reinjection wells for the maintenance of the power plant in April 2003. Gravity changes of a few to several microGals were observed; positive and negative changes were detected in the production and reinjection areas, respectively.

3.2 SP Monitoring

During the summer of 2002, various geophysical measurements (SP, gravity, GPS, tiltmeter and micro-earthquakes) were carried out at Ogiri and some of them resumed in early March 2003 to monitor the changes during the shut-in period. Silver-silver chloride electrodes for the continuous SP measurements were installed at the locations shown in Figure 2. At each of five locations where a 8 m-hole was drilled, one electrode was set at the bottom of the hole and another same-type one was set about 1 m deep near the hole in order to evaluate the rainfall effects.

The computational code of BAYTAP-G (Bayesian Tide Analysis Program – Grouping Model) aims at presumption of tidal components from observation data (Ishiguro et al., 1985; Tamura et al, 1991). The code has other useful functions such as presumption of a trend, a response with

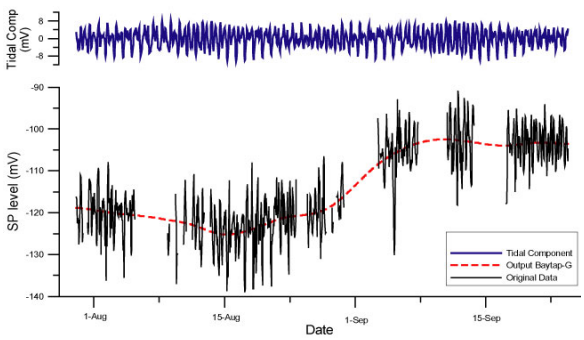

Figure 4: An example of analysis of self-potential records using BAYTAP-G

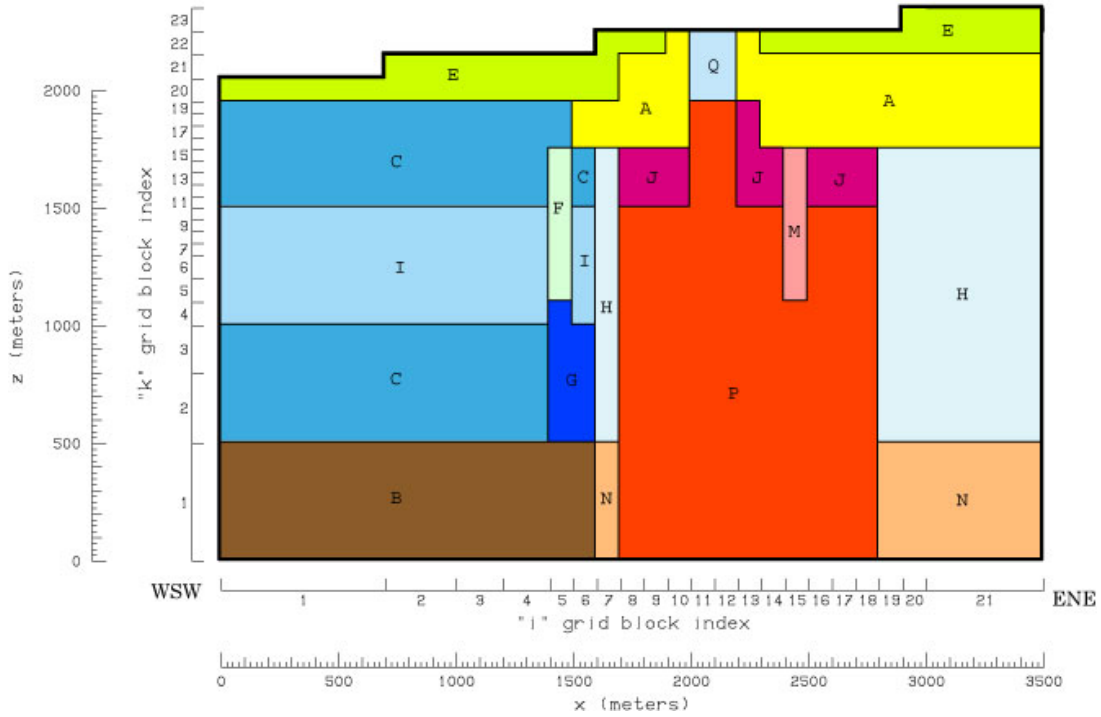

Figure 5: Vertical cross-section of the numerical model along the Ginyu fault. Alphabetic characters indicate rock types with different permeability

atmospheric pressure, and interpolation of missing observation. A Bayesian model and the theory to minimize ABIC (Akaike, 1980) are applied to estimate the trend of the observation. The code is, therefore, a powerful tool for analyzing time series data. This tool, even when time series data are discontinuous, can separate periodic disturbances, such as a tide, from the other signals. It is also possible to interpolate the corrected data, after the removal of the periodic component. An example of the analysis using BAYTAP-G is shown in Figure 4. As shown in this figure, the original SP data were discontinuous and contained much periodic noise. After the subtraction of the tidal component from the original data, SP change was estimated, which is shown by the dashed line, inferring that SP kept almost constant during August and went up by about 20mV in September. Although the Ogiri geothermal field is located far from the coastline (about 20km), SP records are influenced by the tidal signals. The influence of the tidal signal in SP records is often observed in measurements on islands. We do not have a reasonable explanation for why the tidal signal is recorded in the Ogiri field at present.

4. NUMERICAL SIMULATION

4.1 Reservoir Model

Sugihara et al. (2006) modified the 3D reservoir model developed by Yano and Ishido (1995) and the Nittetsu Kagoshima Geothermal, Co. (NEDO, 2002) to explain their gravity data. They adopted finer block sizes for the upper part of the reservoir to reproduce the short-term variation during the 2003 shut-in. The model covers 3500 m × 1900 m area shown in Figure 2 and extends vertically to -1500m b.sl. Block sizes vary from 100 to 1000 m and from 50 to 500 m in the horizontal and vertical directions, respectively. The X-axis is selected along the ENE-WSW direction, i.e. along the strike of the major faults.

Seventeen rock types were selected based on the geological and drilling information (Figure 5). To simplify the simulation procedure, only permeability was varied between different rock types (other rock properties such as porosity, etc. are uniform). Rock properties for the final model are shown in Tables 1 & 2.

Pressure and temperature along the upper surface were held at 0.1 MPa and 20°C, respectively. All vertical side surfaces except the WSW surface were closed at first. Most of the bottom surface was impermeable, but upward conductive heat flux and hot water flows into the reservoir through a few central areas.

Table 1. Parameters Used in the simulation

Parameter	Value	Unit
Porosity	10	%
Density	2500	Kg/m^3
Heat capacity	1050	J/kg-°C
Thermal conductivity	2	W/m-°C
Rate of hot water upflow	46	Kg/s
Temperature of hot water	243-260	°C
Heat flux at bottom surface	0.4	W/m^2

Table 2. Permeability of Each Rock Type

Rock type	Kx darcy	ky	kz	Rock type	kx darcy	ky	kz
A	10^{-5}	10^{-5}	10^{-5}	I	10^{-2}	10^{-2}	10^{-2}
B	10^{-4}	10^{-4}	10^{-4}	J	10^{-1}	10^{-2}	10^{-1}
C	10^{-3}	10^{-3}	10^{-3}	M	10^{-1}	10^{-3}	10^{-1}
E	10^{-3}	10^{-4}	10^{-3}	N	10^{-1}	10^{-2}	10^{-1}
F	10^{-2}	10^{-3}	10^{-2}	P	10^{0}	10^{-1}	10^{-1}
G	10^{-2}	10^{-3}	10^{-2}	Q	10^{-2}	10^{-2}	10^{-2}
	10^{-2}	10^{-3}	10^{-2}				

4.2 Postprocessor Calculations

Sugihara and Ishido (2008) used the geothermal reservoir simulator STAR (Pritchett, 1995) and carried out reservoir simulations of the Ogiri field. The microgravity postprocessor (e.g. Pritchett, 1995) was used to calculate both the long- and short-term changes. To obtain a better match between the calculated and observed long-term gravity changes, they modified the boundary conditions at the ENE side surface so as to allow fluid recharge comparable to the net production rate between 2002 and 2007.

Based upon the updated 3D model, we calculated SP distributions using the self-potential postprocessor (e.g. Ishido and Pritchett, 1999). Figure 6 shows the calculated SP distribution under the natural state condition. A large negative anomaly (shown in white color) appears in the southwest of the production area, which is in good agreement with the results of a SP survey carried out in 1987 (Ishido et al., 1990).

The calculated temporal SP change at an electrode in the central production area is shown in Figure 7. In the beginning SP rapidly decreases, soon turns to increase after about 100 days and becomes almost steady after 1300 days. (After 1300 days, the gravity change calculated by Sugihara and Ishido (2008) also becomes quite steady after the initial rapid decrease.) This calculated result qualitatively reproduces the observed SP changes obtained by the repeated SP mapping in 1998 and 2001 and continuous SP monitoring between 1998 and 2002. However, the calculated amplitude is quite a bit smaller than the observed one. So we need further adjustment of pertinent parameters to get better match.

Three short-term changes at about 2600, 3400, and 4000 days correspond to the shut-ins of production and injection

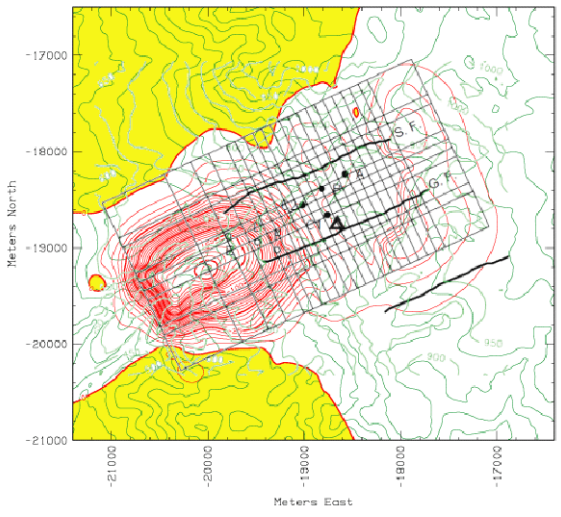

Figure 6: Calculated SP distribution under the natural condition (before the start of the power generation) based upon the 3D numerical fluid flow simulation. The computational grid used for the simulation is the same as shown in Figure 2. Surface traces of two major faults (Ginyu and Sakkogawa faults) are also shown. Positive potential area is shown by yellow

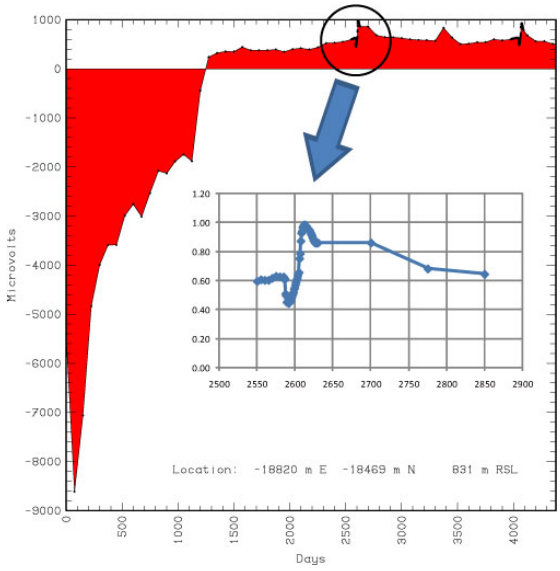

Figure 7: Calculated temporal SP change near the power station. The horizontal axis denotes time in days after the start of the power generation in 1996. Short-term SP change associated with the shut-in in spring 2003 is magnified in the inserted figure (unit of SP in y axis is mV)

wells. The change around 2600 days, which corresponds to the field-wide shut-in in April 2003, is magnified in an inset of Figure 7. SP decreases for about 10 days, then increases and slowly returns near to the steady level by taking about 200 days. Such SP change was predicted by the calculation based upon a simple two dimensional model (Ishido et al., 2005).

Figure 8 shows SP changes observed by the continuous measurement in spring 2003. We observed an SP increase in the production area in early April corresponding to the field-wide shut-in. However, the SP changes were small in magnitude and disturbed by various noises. Before going to further matching between the calculated and observed changes, we need to clarify the noise sources and apply an appropriate noise reduction technique to get more definite conclusions.

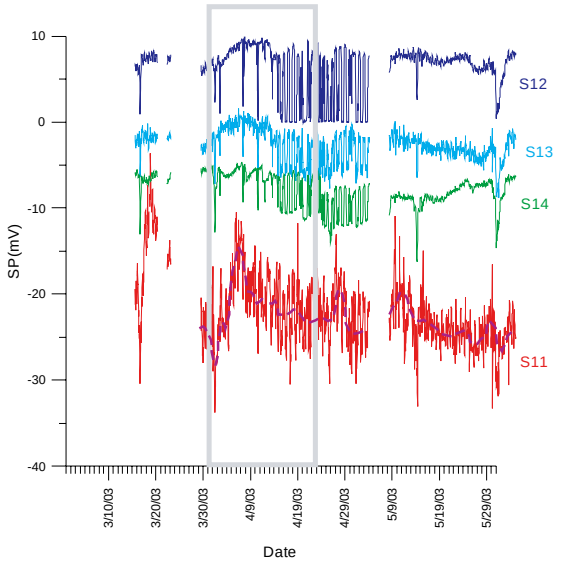

Figure 8: Observed SP changes during the shut-in for the annual maintenance of the power plant in April, 2003. The shut-in period is indicated by the grey rectangle. The site of S-11 is located on the surface near the production zone. Other sites are relatively far away from the production zone. SP signal on the S-11 site decreased at the beginning of the shut-in and then increased

CONCLUSIONS

The self-potential postprocessor was applied to the 3D reservoir model of the Ogiri geothermal field, which was calibrated against the observed changes in microgravity between 2002 and 2007 (Sugihara and Ishido, 2008). The calculated SP variation is qualitatively consistent both with the relatively long-term changes obtained by the repeated surveys in 1998 and 2001 and the short-term changes detected by the continuous measurement between March and May 2003.

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REFERENCES

Akaike, H.: Likelihood and the Bayes procedure, In Bayesian Statistics, eds. J.M.Bernardo, M.M.DeGroot, D.V.Lindley and A.F.M.Smith, University Press, Valencia, Spain, 143-166(1980).

Goko, K.: Toward Sustainable Steam Production; the Example of the Ogiri Geothermal Field. J. Geotherm. Res. Soc. Japan, 25, 151 (in Japanese with English abstract) (2004).

Horikoshi, T., Yamasawa, S., Ide, T., and Tosha, T.: NEDO's Project on Development of Technology for Reservoir Mass and Heat Flow Characterization. (1) Project Outline and Techniques to Improve the Reservoir Model. Geotherm. Resour. Coun. Trans., 25, 641(2001).

Ishido, T., and Pritchett, J.W.: Numerical Simulation of Electrokinetic Potentials Associated with Subsurface Fluid Flow, *J. Geophys. Res.*, *104*, (1999), 15247-15259.

Ishido, T., Kikuchi, T., Yano, Y., Sugihara, M., and Nakao, S.: Hydrogeology Inferred from the Self-Potential Distribution, Kirishima Geothermal Field, Japan. Geotherm. Resour. Coun. Trans., 14-part II, 916 (1990).

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 Geotherm. Cong. 2005, Proc., 1160.

Ishiguro, M. and Tamura, Y.: BAYTAP-G in TIMSAC-84, In Computer Science Monographs, 22, 56-117, The Institute of Statistical Mathematics, Tokyo(1985).

Pritchett, J. W.: STAR: A Geothermal Reservoir Simulation System. World Geotherm. Cong. 1995, Proc., 2959 (1995).

Sugihara, M., Ishido, T. and Horikoshi, T.: Short-term Microgravity Changes due to Shut-in of Production and Reinjection Wells, the Ogiri Geothermal Field, Japan. Geotherm. Resour. Coun. Trans., 30, 965 (2006).

Sugihara, M. and Ishido, T. (2008) Geothermal Reservoir Monitoring with a Combination of Absolute and Relative gravimetry, Geophysics, 73, WA37-47.

Tamura, Y., T. Sato, M. Ooe and M. Ishiguro, 1991, A Procedure for tidal analysis with a bayesian information criterion, Geophys. Jour. Int., 104, 507-516.

Therm. Nuclear Power Eng. Soc.: Current Status and Trend of the Geothermal Power Generation in Japan, 99p(2007).

Tosha T., Ishido, T and Sugihara, M.: Geophysical monitoring with reservoir simulation in a geothermal field, Japan, Handbook and Proc. of the 30th New Zealand Geothermal Workshop,155-160 (2008).

Yano, Y., and Ishido, T.: Numerical Modeling of the Evolution of Two-Phase Zones under a Fractured Caprock, *Geothermics*, 24, (1995), 507-521.