

## Reservoir Monitoring in the Okuaizu Geothermal Field Using Multi-Geophysical Survey Techniques

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### ABSTRACT

To obtain a better understanding and more precise forecast of the geothermal reservoir, reservoir monitoring using multigeophysical survey techniques is an effective way to build a more realistic model than conventional methods. We have carried out gravity and self-potential (SP) monitoring and introduced these data to constrain reservoir simulations in the Okuaizu geothermal field in northeastern Japan, where a 65MWe geothermal power station has been operated since 1995.

Gravity changes have been monitored since 1992. Although a rapid reduction in gravity was observed for the first three years of operation, change have become smaller since 1998. SP monitoring has been carried out by repeated surveys and by continuous measurements. As a result of the 1996 survey, the dominant SP anomaly of positive polarity over the high-temperature zone in the natural state was found to disappear. Continuous monitoring afterwards revealed changes in SP associated with the field-wide shut-in of about one month in 1998 and 2002.

History-matching studies are underway using these data from geophysical monitoring as constraints on reservoir models.

### 1. INTRODUCTION

Precise modeling is very important for understanding of a geothermal reservoir, for reservoir evaluation at early stages of the development, for stable operation of the power station, and for planning of fluid production from additional wells in and around the developing area. To reduce uncertainty of any reservoir model, geophysical monitoring data is useful to constrain the models.

To study the feasibility of reservoir monitoring by simultaneous continuous/repeat measurements of gravity and SP for history-matching of reservoir models, Ishido et al. (2005) performed numerical simulations based upon a hypothetical three-dimensional reservoir model and calculated changes in microgravity and self-potential on the ground surface caused by changing reservoir conditions. It was shown from the calculation results that a combination of long-term repeat microgravity surveys and short-term continuous SP measurements at the time of field wide shut-in has a considerable promise to provide useful additional constraints in history-matching studies.

The Geological Survey of Japan (GSJ), Okuaizu Geothermal Co., Ltd.(OAG) and Tohoku Electric Power Co., Inc. (Tohoku EPCO) have carried out a collaborative research program "System Integration of Various Geophysical Measurements for Reservoir Monitoring"

since 2002 by choosing the Okuaizu geothermal field as one of the model fields. This cooperative research aims to make practical application of the results of another geothermal R&D project "Development of Technology for Reservoir Mass and Heat Flow Characterization" (Horikoshi et al., 2001; Yamazawa et al., 2001).

### 2. OKU-AIZU GEOTHERMAL FIELD

Okuaizu geothermal field is located in northeastern Japan. Following a reconnaissance survey for mining in 1956, geological, geophysical and geochemical surveys of the geothermal resource were carried out from 1974, and Yanaizu-Nishiyama geothermal power station commenced its operation in May 1995 with 65MW of electrical production (Saeki, 1999).

The geothermal features of this area is characterized by NW-SE trending vertical faults (Figure 1). Surface hydrothermal manifestations, the distribution of low resistivity, SP and soil gas anomalies and the locations of lost circulation in exploration wells are aligned along these faults (NEDO, 1985; Nitta et al., 1987). The survey data indicates that the geothermal reservoir in this area is strongly controlled by vertical fault zones and the upflow of geothermal fluid takes place along two NW-SE faults, namely the Sarukurazawa Fault and the Chinoikezawa Fault. The production wells target these two faults as a production zone. The injection zone is expected to be around the Oisawa fault, which is permeable, but at lower temperature (Saeki, 1999).

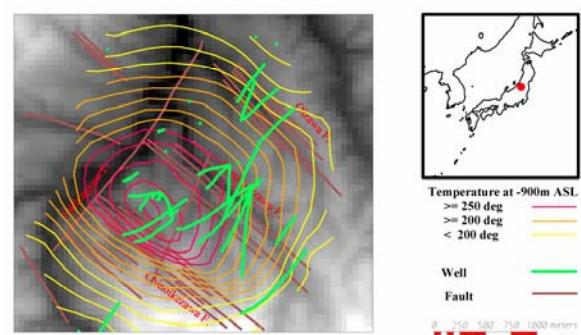


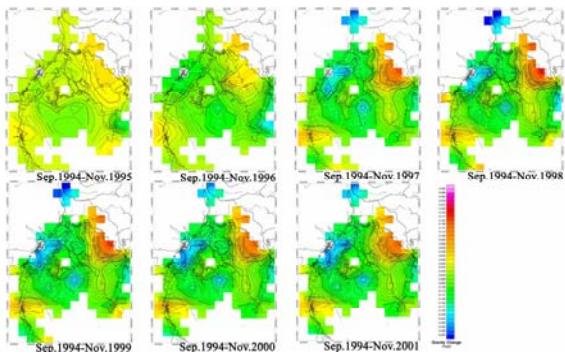
Figure 1: The location map of the Okuaizu geothermal field. Shading : topography, brown line : fault, green line : well, contour line : temperature at -900 m ASL.

### 3. GEOPHYSICAL DATA

#### 3.1 Gravity Change

Gravity monitoring is useful to estimate subsurface mass changes in geothermal reservoir due to fluid production.

In Okuaizu geothermal field, OAG and Tohoku EPCO have carried out annual gravity monitoring with leveling surveys at 83 gravity stations since September 1994, about a half year before fluid production began. In 1997-2002, NEDO carried out a geothermal R&D project “Development of Technology for Reservoir Mass and Heat Flow Characterization”, and gravity monitoring in this area was carried out in this project as a part of research on gravity monitoring techniques by OAG and Tohoku EPCO. Gravity surveys were conducted nine times since 1997 with these gravity stations and 53 additional stations in the study area. Scintrex CG-3M gravimeters were introduced for gravity measurement and a GPS survey was adopted instead of a leveling survey for elevation change detection to reduce survey cost. Combining the results with the conventional monitoring surveys in 1994-1996, gravity changes in and outside the production and reinjection areas were determined for seven years of commercial steam production (NEDO, 2002).

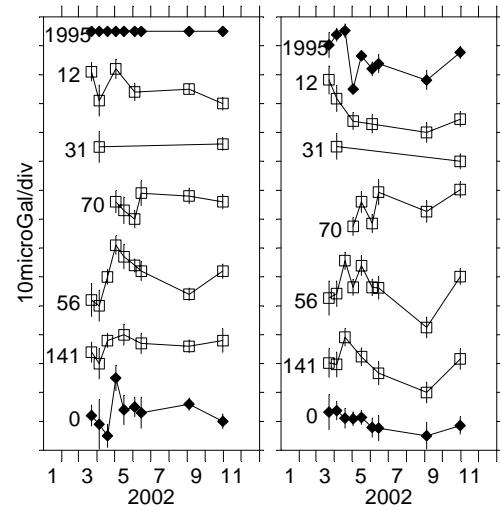


**Figure 2: Gravity change around production and injection areas since 1994 (gravity difference from the measurements in 1994) [NEDO, 2002]**

The production area along the NW-SE faults showed substantial gravity reduction after the beginning of steam production. However, gravity changes have been getting smaller year by year. In particular, since 1998, very small gravity changes have been observed (Figure 2) (NEDO, 2002).

From the results of eight seasonal and annual gravity surveys, the regional pattern of the gravity changes related with the one-month field-wide shut-in in 1998 was observed. To grasp more detailed feature of gravity changes associated with the field-wide shut-in, gravity surveys were repeated with a short interval (i.e. 2 - 3 weeks) around the production area in 2000 and in 2001. However, no significant gravity change was found at the time of production suspension in these surveys (NEDO, 2002). These results suggest that changes in reservoir mass due to fluid production have been getting smaller even during an event such as temporal production suspension (NEDO, 2002).

Since 2002 GSJ have carried out absolute gravity measurements to obtain a precise reference for monitoring in this field. With an absolute gravity datum, small gravity change can be detected. Figure 3 shows the comparison between the reference method, e.g. a conventional method to use stable reference stations outside of the target area as reference and a hybrid method using an absolute gravity measurement to obtain the reference value.

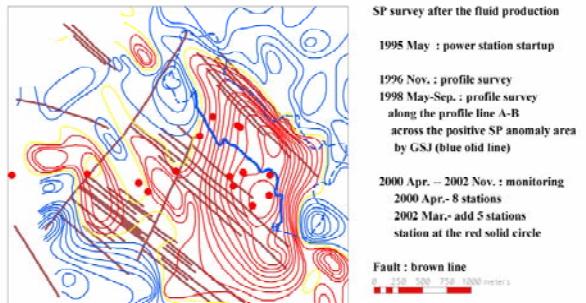


**Figure 3: Temporal gravity variation at each gravity station in 2002 (Sugihara, 2003). left: to empirical datum (1995 is assumed as the reference station); right: to absolute datum.**

### 3.2 Self-potential (SP) data

SP anomalies of positive polarity have been found over high temperature upflow zones in many geothermal and volcanic areas. The most likely cause of these positive anomalies is believed to be the streaming (electrokinetic) potential generated by hydrothermal circulation (Ishido et al., 1989).

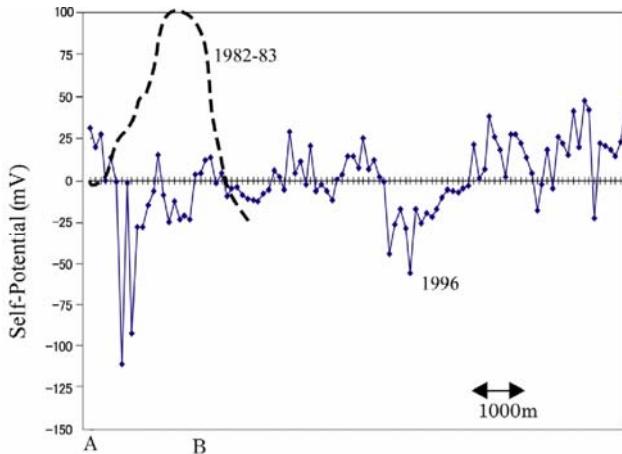
In 1982-1983, the SP distribution in the natural state before fluid production was measured over this area as a part of the Geothermal Development Promotion Survey by NEDO (NEDO, 1985; Nitta et al., 1987). A dominant SP anomaly of positive polarity over the high-temperature zone was detected from this survey (Figure 4)



**Figure 4: Self-Potential distribution in 1982-1983 (before the fluid production). contour lines in red(positive), yellow (zero), cyan (negative) : self-potential in 1982-1983 (Nitta et al., 1987); brown line: fault; blue solid line: profile line for the SP profile survey in 1996 and 1998; red dot: continuous SP monitoring station from 2000-2002.**

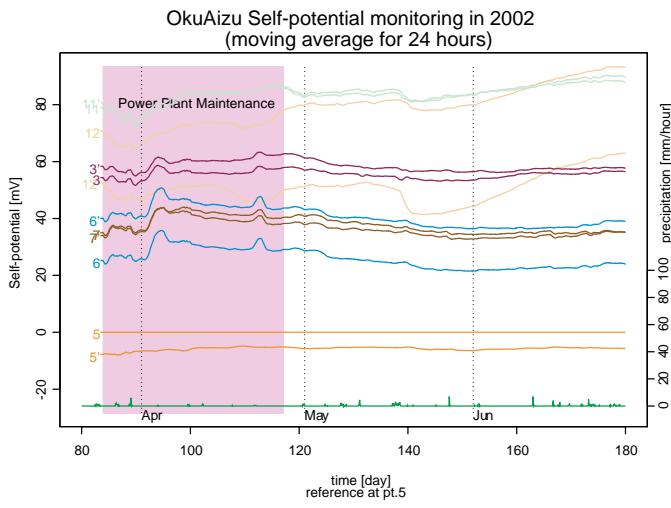
After the start-up of the fluid production, GSJ carried out repeat SP surveys in November 1996 and May-September 1998 along a profile line across this anomaly area (Tosha et al., 2000). Since April 2000, GSJ have started continuous SP monitoring at eight stations around this profile line to obtain detailed SP variation, and added five stations in March 2002. At each station, two or three Pb-PbCl<sub>2</sub>

electrodes are buried at 1 meter depth close to each other. Multiple electrodes are set to distinguish real SP variation and offset-drift of each electrode.



**Figure 5: SP profile along the profile line in Figure 3 (Tosha et al., 2000). Dashed line: natural state in 1982-83; solid line: in 1996, 1.5 year from the commencement of the power station**

The positive SP anomaly over the high-temperature zone in the natural state was found to disappear in 1996, after 1.5 years of the fluid production (Figure 5). In 1998, 2000 and 2002, fluid production was suspended for a short term (less than 1 month) due to field wide shut-in for periodic power station maintenance. A small positive anomaly appeared during the field-wide shut-in period, and disappeared after the re-start of fluid production in 1998 (Tosha et al., 2000). In 2002, SP at the stations in the low resistivity zone above high-temperature zone increased about 5 mV just after the shut-in (Figure 6). In 2000, the heavy rainfall just before the field wide shut-in period disturbed the SP variation and it was not possible to distinguish the SP variation due to the production-rate change (Nishi et al., 2003).



**Figure 6: SP variation related to field wide shut-in in 2002. SP continuous monitoring was carried out at the stations in Figure 1. Each station has two or three electrodes to be measured. The shaded area shows the power station maintenance period. As this period includes well operation stage (about one week), real field wide shut-in period is in the middle of this shaded interval.**

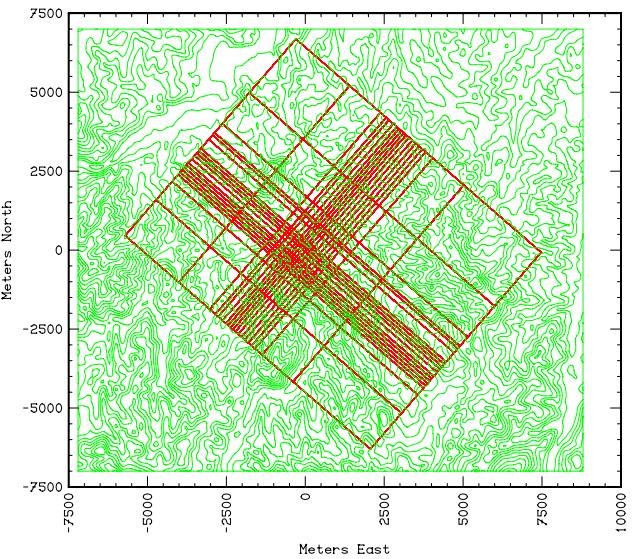
#### 4. RESERVOIR SIMULATION

In the Okuaizu geothermal field, gravity shows rapid decrease at the beginning of the fluid production and the variation rate becomes gradual with time. The dominant positive SP anomaly over the high temperature zone in the natural state disappeared after the fluid production, although some recovery seems to appear during the fluid production suspension.

Ishido et al. (2005) showed some results of numerical simulation with calculations of gravity and SP variations for a three-dimensional hypothetical model of a high-temperature fractured reservoir, which can be seen as a simplified model of Okuaizu reservoir. The results of the calculation suggest that a high permeability fractured model could explain the long-term and short-term variations of gravity and SP observed in the Okuaizu area.

In this model, the high-temperature upward fluid flow produces a positive SP anomaly in the natural state. The production-induced fluid flow replaces this upflow resulting in the disappearance of the positive anomaly after commencement of fluid production. The growth of a two-phase zone results in the gravity reduction in the production area. SP recovers during the shut-in of production wells due to reduction in the production-induced fluid flow (Ishido et al., 2005).

To apply this technique and conceptual model to real monitoring data of the Okuaizu area, and to refine the techniques for “System integration of various geophysical measurements for reservoir monitoring”, we have carried out numerical simulations of Okuaizu reservoir using gravity and SP data as constraints on the models.



**Figure 7 Plan map of the simulation grid.**

The starting model for the present numerical simulation studies is the final numerical model developed by Tohoku EPCO and OAG using the simulation code TOUGH2 under the NEDO project (Figure 7) (NEDO, 2002). This model covers a volume of  $10.3 \text{ km (NW-SE)} \times 8.25 \text{ km (NE-SW)} \times 2.9 \text{ km (depth)}$  with  $19 \times 19 \times 10$  blocks. The block size ranges from  $100 \times 100 \times 100 \text{ m}^3$  to  $2250 \times 3250 \times 300 \text{ m}^3$ . High-temperature fluid is supplied beneath Chinoikezawa fault, and flows upward through the fault up to -400 meter ASL. At -400m ASL, the flow direction turns to NE along the Takiyagawa fault. History matching between the

observed and calculated gravity changes was carried out to calibrate the reservoir model after the natural state simulation and history matching of wellhead enthalpies. This study showed that expansion of the two-phase region is required during production in order to reproduce the observed changes in gravity (NEDO, 2002). Although this model explained the gravity change of long-wavelength, it could not achieve a good fit to the short wavelength component.

The numerical model was converted into the STAR format as the reservoir simulator used for our project is the STAR code (Pritchett, 1995) ported on Windows PC (NEDO, 2003). Source/sink data and boundary conditions were also imported. We have carried out history-matching of gravity and SP monitoring data in addition to production enthalpy data. To compare the simulation result and geophysical data, the postprocessors for STAR developed under the NEDO project (Ishido and Pritchett, 1999; Ishido and Pritchett, 2003; NEDO, 2003) were used. These postprocessors calculate changes in geophysical observables caused by changing reservoir conditions. Although it is still in progress to obtain better matching with all available data, an example of the calculated results is shown in Figures 8 and 9.

## 5. CONCLUSION

In the Okuaizu geothermal field, we have carried out gravity and SP monitoring in order to use these data to constrain reservoir models. The observed gravity change shows a rapid reduction after the beginning of production, and very small decrease after three years of field operation. The dominant SP anomaly of positive polarity over the high-temperature zone, which was present under the natural state condition, disappeared after 1.5 years of fluid production. As for SP, small but obvious changes were observed during the field-wide shut-in periods. We could detect 5 mV short-term SP variations due to production suspension by continuous monitoring in 2002.

Numerical simulation based upon gravity and SP data has been carried out, and results from preliminary models suggest that expansion of the two-phase zone during production has an important role in reproducing the changes in not only gravity but also SP as well.

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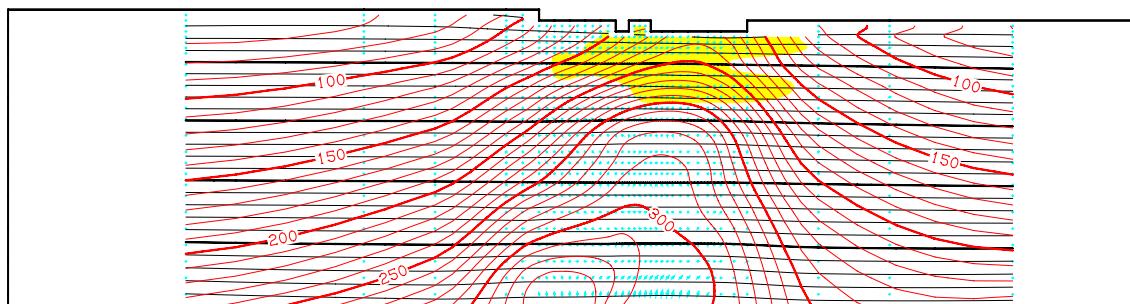
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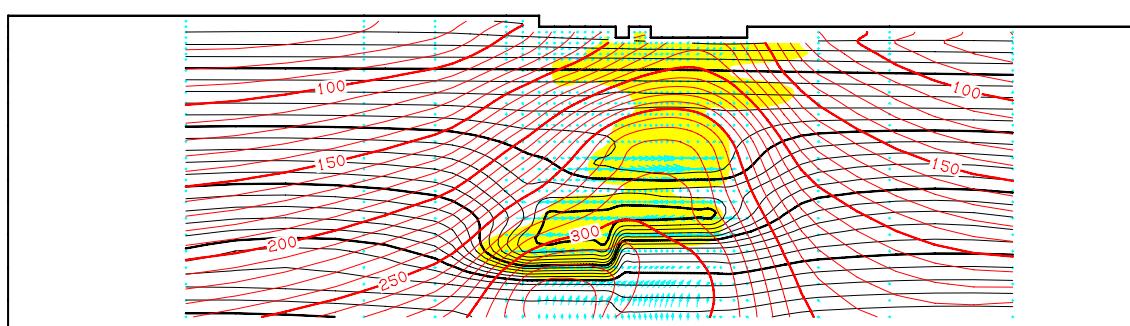
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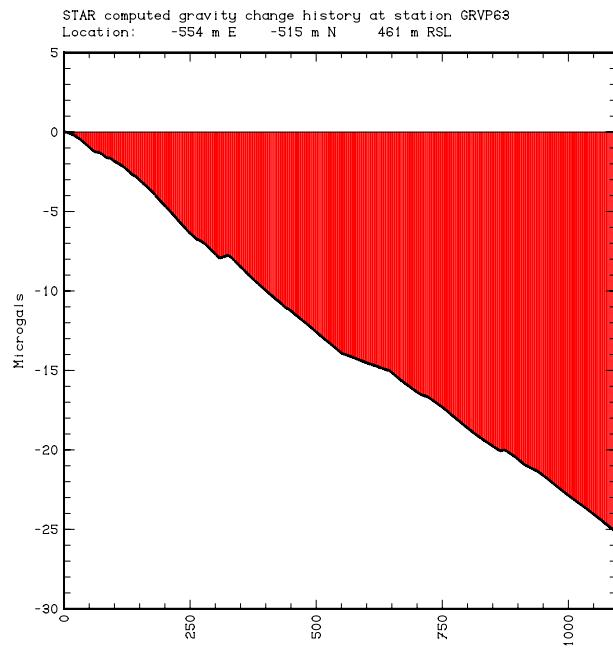
Natural State



3 years from fluid production

NEDO-350deg-Grant-NoNaCl-OrgPRMonGEOfile-RUN3-PorousTighten

**Figure 8 Example of simulation result. Upper: natural state, Lower: 3 years from fluid production. Red contour: temperature, black contour: pressure, blue arrow: fluid flow, yellow shade: two-phase zone**



**Figure 9 Example of gravity change at GRVP62, a gravity station above Chinoikezawa fault.**