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Reservoir Monitoring by Continuous Self-Potential Measurements and a Preliminary History Matching Study, the Ogiri Geothermal Field, Japan

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ABSTRACT

We have been conducting continuous self-potential (SP) measurements at the Ogiri geothermal field, southwest Japan, where a geothermal power plant is operating. The objective of the measurements is to detect SP variations caused by changing reservoir conditions and to use the observed data in history-matching studies of reservoir models. We observed short-term changes in SP during the production test of exploratory wells at the Shiramizugoe field, located about 2 km southeast of the Ogiri field in 2002, and changes in SP associated with field-wide flow-rate change during the maintenance period of the power plant in 2003. We present the observed SP data and interpret them on the basis of reservoir simulation and the EKP-postprocessor calculations.

1. INTRODUCTION

The Ogiri geothermal area is located on the western slope of the Kirishima-volcanoes in northwestern part of the Kagoshima prefecture, Kyushu, Japan. The New Energy and Industrial Technology Development Organization (NEDO) carried out a self-potential (SP) survey of the Ogiri area in 1998. Comparing this result to that in 1987 (Ishido et al., 1990), decreases in SP were detected both in the production and reinjection areas. These changes are thought to be induced by the exploitation operation of the Ogiri geothermal power station (30 MW) started in 1996. In addition to repeat surveys, continuous SP monitoring was carried out by NEDO from 1998 through 2001 under a geothermal R&D project, "*Development of Technology for Reservoir Mass and Heat Flow Characterization*" (see e.g., Horikoshi et al., 2001; Yamasawa et al., 2001).

In 2002, the Geological Survey of Japan (GSJ) started a new cooperative research program, "*System Integration of Various Geophysical Measurements for Reservoir Monitoring*", focused on the Ogiri area as one of the two model fields, to make practical applications of the results of the above mentioned NEDO/GSJ project. During the summer of 2002, various geophysical measurements (SP, gravity, GPS, tiltmeter and micro-earthquakes) were carried out in the Ogiri and the adjacent Shiramizugoe (just south of Ogiri) areas. Simultaneously, short-term production tests involving new exploratory wells drilled in the Shiramizugoe area were carried out under NEDO's geothermal survey program, "*Geothermal Development Promotion Survey*". In collaboration with Nittetsu-Kagoshima Geothermal (NKG), monitoring resumed in early March 2003 and was continued for one year. In April 2003, the production rate was substantially reduced for Ogiri power station maintenance. We plan to carry out history-matching studies using these data, supported by various reservoir engineering data (provided by NKG) and earlier SP results (a 1987 SP survey by GSJ/NEDO and 1998–2002 continuous/repeat SP measurements by NEDO).

In this paper we will focus on the results of SP measurement in 2002 and discuss changes in SP associated with the short-term production tests of exploratory wells in the Shiramizugoe area on the basis of preliminary reservoir simulations.

2. SELF-POTENTIAL DATA

The SP observation system and the data obtained during the summer of 2002 were described in detail by Tosha et al. (2003). Here, we summarize the main results of the observations.

Figure 1: Location of electrodes for continuous SP measurements in the Ogiri and Shiramizugoe Areas.

2.1 SP Network for Ogiri/Shiramizugoe Areas

The SP observation network in the Ogiri and Shiramizugoe areas is illustrated in Fig. 1. We added six electrodes (shown by red circles) around the exploratory wells in the Shiramizugoe area to the Ogiri network, which consisted of about fifty electrodes (shown by black squares) originally deployed by NEDO. All of the electrodes used were non-polarizing $Pb\text{-}PbCl_2$ type manufactured by the Phoenix Geophysics. The stability of the electrodes was confirmed during a three-year continuous measurement carried out at the Ogiri field. Among the six newly added electrodes, electrodes S-01 and -02 and electrode S-05 were located near to the wellheads of SZ-4 and SZ-5 respectively. Other electrodes (S-03, -04 and -05) were distributed to cover the reservoir region which was expected to be present along the Shiramizugoe fault (Goko, 2000).

Insulated wires made of copper from each new electrodes were gathered to the same recording system as used for the Ogiri observation network. In the Ogiri area there often happens thunder storm especially in summer and winter, resulting in frequent damages of the scanner used for the recording system. To minimize this kind of damage, the power supply was disconnected from the survey system when the occurrence of thunder storm was expected, resulting in considerable breaks in the recorded data.

2.2 Observed SP Changes Associated with Production Tests

Production tests of two Shiramizugoe wells, SZ-4 and SZ-5, were carried out in August 2002. Well SZ-5 started to flow at 12:10 on August 1 and was shut-in at 6:00 on August 6 (the flow rate was almost constant at about 300 t/h). Subsequent to the SZ-5 test, the flow test of well SZ-4 was carried out from 11:07 on August 12 through 17:57 on August 26 (the flow rate was not constant as shown in top of Fig.2). In both cases, the separated hot water was injected into the western part of Shiramizugoe fault by using well SZ-3.

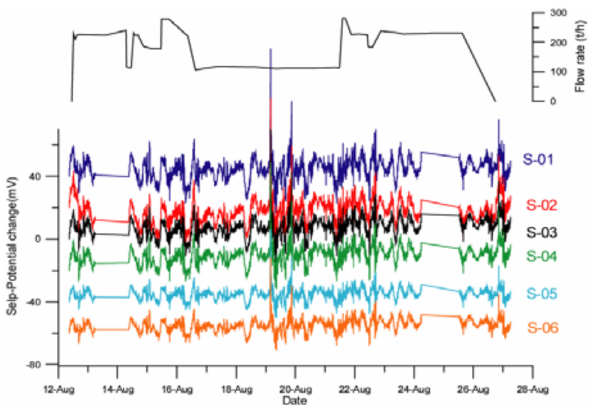

Figure 2: Raw SP data for electrodes deployed in the Shiramizugoe area. Also shown in top is the flow-rate of well SZ-4.

Fig. 2 shows recorded potentials of six electrodes S-01 through -06 referring to a remote electrode (which was used as reference in the Ogiri network) for the period of SZ-4 production. As seen in the figure, short period components such as tide-related ones are dominant, which makes it difficult to detect small signals.

In the present study, we adopt BAYTAP-G (Bayesian Tide Analysis Program – Grouping Model) (Ishiguro et al., 1985; Tamura et al, 1991) for the data processing. BAYTAP-G allows us to estimate the trend of observed time series in addition to do tidal component analysis by applying a Bayesian model and minimizing ABIC (Akaike, 1980). The code is a powerful tool in analyzing time series data and can be used to interpolate the data in addition to removing tidal components etc. An example of BAYTAP-G application is shown in Fig. 3. Although there are many gaps in the original SP data (due to above mentioned thunder-related problem), a smooth and continuous trend (shown by dashed line) is obtained.

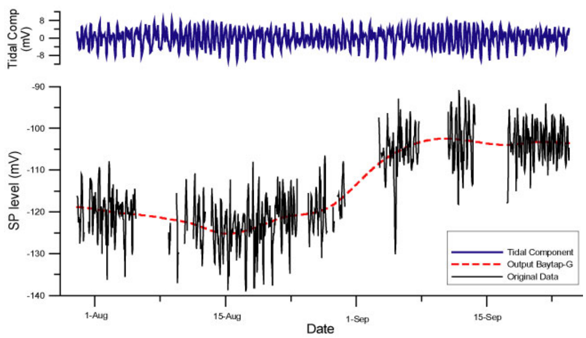

Figure 3: An example of analysis of SP data using BAYTAP-G.

Fig. 4 shows the trends which are obtained by applying BAYTAP-G to the raw data for electrodes S-01 through -06. The trend of S-05 is almost constant and those of S-03, -04 and -06 gradually increase during the three months from early August through the end of October. In contrast to these behaviors, the trends of S-01 and -02, which were located close to the wellhead of SZ-4, first decrease just after the start of production test and then recover in late August. These changes seem to be correlated with the production tests of wells SZ-5 and SZ-4 (although another substantial change is seen for S-02 in late September). In the next section, we will show the results of numerical simulation, which was carried out to interpret the observed SP changes.

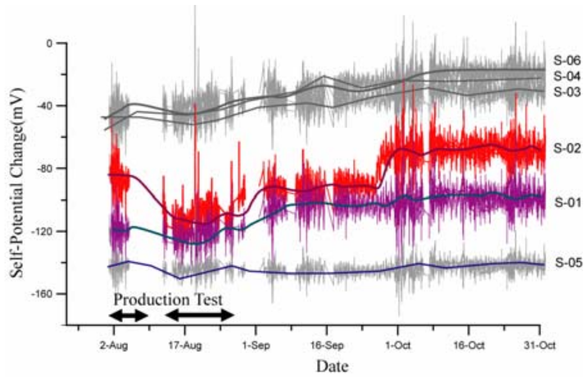

Figure 4: Trends of SP for electrodes deployed in the Shiramizugoe area. The intervals of production tests are shown in bottom.

3. NUMERICAL SIMULATION OF SP CHANGES

3.1 Reservoir Model

The reservoir model used here is essentially the same as the conceptual model for numerical studies of the natural evolution of a two-phase geothermal reservoir which has formed along the Ginyu fault in the Ogiri area (Yano and Ishido, 1995). Since the Shiramizugoe fault develops in the same geological setting as that of the Ginyu fault in the western slope of the Kirishima-mountains, we adopt this model to calculate changes in reservoir condition which are expected to be caused by short-term production tests of wells SZ-4 and -5.

The model represented by the two-dimensional vertical cross-section shown in Fig. 5 incorporates the general structural features of the Ginyu and Shiramizugoe fault sytems. The high-permeability reservoir (*A* in Fig. 5) is overlain by the low-permeability altered caprock (*C*). Hot recharge water is assumed to enter the reservoir from below through a permeable conduit (*E*). A permeable horizontal conduit (*H*) allows for lateral mass outflow. The rocks *S* and *B* surrounding the reservoir are more permeable than the caprock, but the permeability of rock *B* is low enough that conduction is the dominant mode of heat transfer. All rock formations are assumed to be porous media; their properties range from 0.01 to 0.1 in porosity and from 0.01 mdarcy (for *C*) to 100 mdarcy (for *A*, *E* and *H*) in permeability. All exterior boundaries except the top surface and a part of the western vertical surface, where the horizontal conduit intersects, are closed; pressure and temperature are maintained at 1 bar and 20 °C respectively along the top boundary.

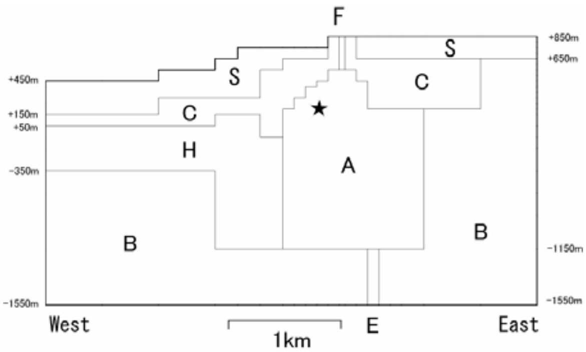

Figure 5: Two-dimensional reservoir model used for numerical simulation of the short-term production test.

A source of high-temperature "magmatic water (T_0=260 °C, M_0=36 kg/s)" was imposed at the bottom of deep conduit; the evolution of the hydrothermal convection system was then simulated using the STAR geothermal simulator. The system reached quasi-steady state after around 5000 years; in Fig. 6, the distributions of temperature, vapor saturation and fluid mass flux are shown for 6000 years.

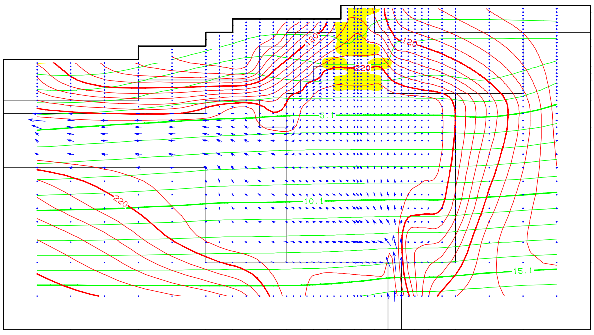

Figure 6: T Distributions of temperature, vapor saturation and fluid mass flux under natural state condition.

3.2 Calculation of Change in SP due to Fluid Production

The STAR simulator was also used to perform a forecast of the consequences of short-term production, starting from the natural-state model described above as the initial conditions. All boundary conditions and rock properties were the same as used to calculate the natural-state. One hypothetical production well was incorporated within the model (the location of feedpoint is shown by a star symbol in Fig. 5). A constant total flowrate of 200 ton/hour was assumed to be withdrawn from the production well from t=10 to t=40 days. In Fig. 7, the distributions of temperature, vapor saturation and fluid mass flux are shown for t=50 days. The vapor zone expands downward owing to the pressure decline caused by fluid production.

The EKP postprocessor (Ishido and Pritchett, 1999) was next applied to calculate SP changes induced by fluid production. The reservoir simulation grid (called as "RSV"-grid) is embedded in the "SP"-grid, which has a larger spatial extent than the "RSV"-grid. Within the portion of the "SP"-grid overlapped by the "RSV"-grid, the distribution of electrical conductivity is obtained directly from "RSV"-grid values. Elsewhere within the "SP"-grid, the electrical conductivity is user specified and time invariant. For the SP calculation, the magmatic fluid is assumed to contain NaCl; the concentrations are proportional to the mass fraction of magmatic dilute tracer, and NaCl is 0.02 mol/l in the pure upflowing magmatic fluid entering from below. The fresh water is assumed to contain dilute NaCl (0.002 mol/l).

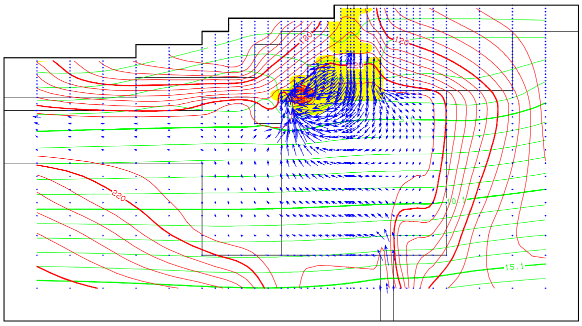

Figure 7: Distributions of temperature, vapor saturation and fluid mass flux after one-month production test.

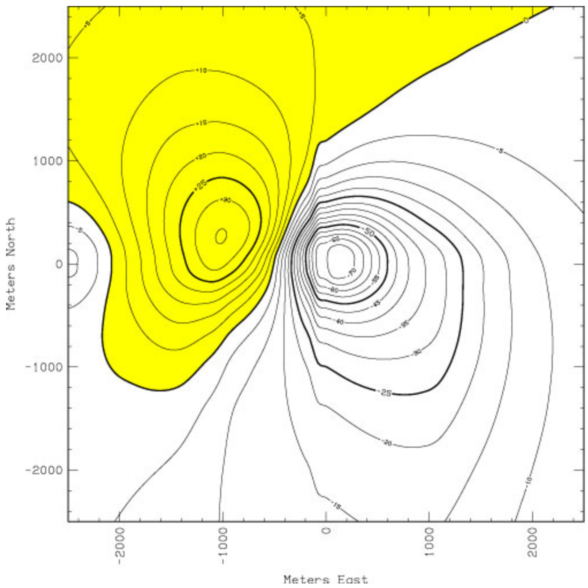

Figure 8: Calculated changes in SP between t=0 and t=50 days on the ground surface. Fluid production takes place from t=10 to t=40 days.

Fig. 8 shows the calculated distribution of SP change on the ground surface between t=0 and t=50 days. In the present calculation, the two dimensional RSV-grid, which has the thickness of 250 m, is embedded in the SP-grid along the plane of Y=0. However, the calculated result is not symmetrical in respect to the line of Y=0. This is because we assumed different conductivities for the SP-grid between the northern and southern sides of the RSV-grid. In the southern side, the high conductivity associated with the caprock (0.1 S/m) is assumed to extend from Y= -125 to Y= -1000 m, while no such high conductivity is assumed in the northern side. This assumption is based upon the resistivity structure in the Shiramizugoe area revealed by the MT survey. As seen in Fig. 8, the area of SP decrease extends more to the south than to the north. In the present observation, almost all electrodes were deployed on the northern side of the reservoir penetrated by wells SZ-4 and -5 (see Fig. 1). This is a possible explanation why no change in SP was observed except for electrodes S-01 and -02.

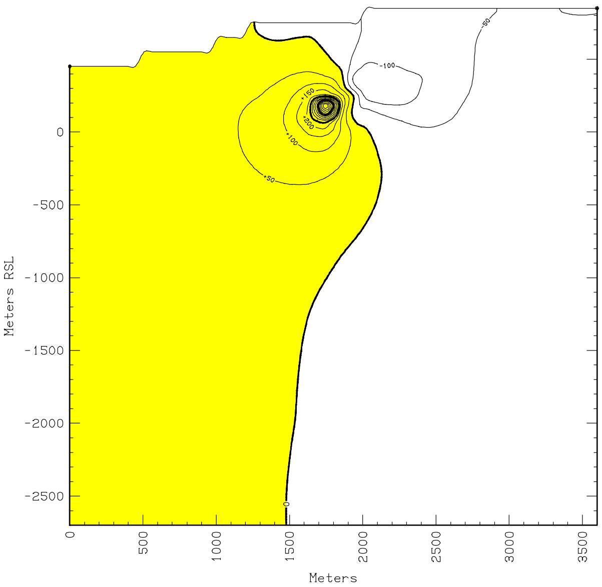

Figure 9: Calculated changes in SP between t=0 and t=50 days on the ground surface. Fluid production takes place from t=10 to t=40 days.

Fig. 9 shows vertical contour plot of change in electrical potential between t=0 and t=40 days. High potential region (i.e. source of conduction current) appears corresponding spatially to the feedpoint of production well, which is responsible for the SP increase in the western area shown in Fig. 8. At shallower levels low potential region (i.e. sink of conduction current) appears, which is produced by downward flow of the liquid phase associated with vigorous boiling taking place in the expanding two-phase zone (see Ishido and Pritchett, 2003). This sink of conduction current brings about the substantial SP decrease in the southeastern area shown in Fig. 8.

As seen in Fig. 8, no substantial change in SP occurs in the northern side of the reservoir, e.g. at X=0 and Y=1000 m. However, the presence of electrically-conductive well casings would distort the potential around them. If we assume a hypothetical well which is drilled from a point at X=0 and Y=1000 m on the ground surface and deviated so as to pass through the zone of current sink shown in the vertical contour plot (Fig. 9), substantial SP change appears around the wellhead (see Fig. 10). This explains why we observed obvious SP decrease and recovery only at electrode S-02, which was only ~30 m apart from the wellhead of SZ-4.

4. CONCLUDING REMARKS

We have carried out various geophysical measurements (SP, gravity, GPS, tiltmeter and micro-earthquakes) in the Ogiri geothermal area under a cooperative research program, *"System Integration of Various Geophysical Measurements for Reservoir Monitoring"*. We detected changes in SP caused by short-term production tests involving new exploratory wells drilled in the adjacent Shiramizugoe area. The observed results can be interpreted on the basis of preliminary numerical simulation of electrokinetic potentials caused by changing reservoir conditions. We are now carrying out history-matching studies using the various geophysical monitoring data, especially taken at the occasion of field-wide flow-rate change during the maintenance period of the Ogiri power station in April 2003, supported by various reservoir engineering data (provided by NKG) and earlier SP results (a 1987 SP survey by GSJ/NEDO and 1998–2002 continuous/repeat SP measurements by NEDO).

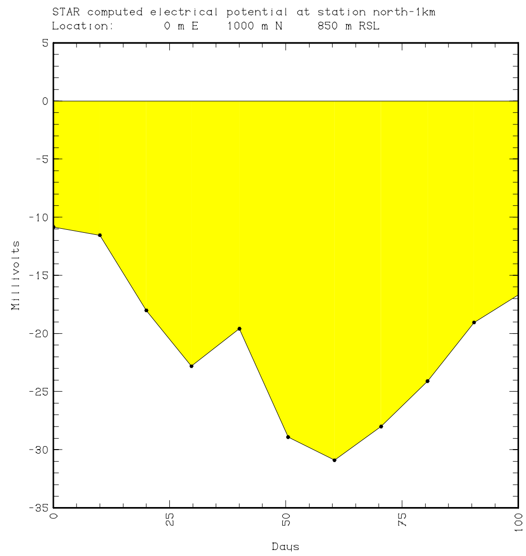

Figure 10: Calculated changes in SP between t=0 and t=50 days on the ground surface. Fluid production takes place from t=10 to t=40 days.

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