PROCEEDINGS, Twenty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 27-29, 2003
SGP-TR-173

USING SELF-POTENTIAL MONITORING TO HELP CHARACTERIZE THE ONIKOBE GEOTHERMAL RESERVOIR IN JAPAN

Chitoshi Akasaka[1], Shigetaka Nakanishi[1], Shigeo Tezuka[1], Tsuneo Ishido[2] and John W. Pritchett[3]

1.Electric Power Development Co., Ltd,
Tokyo, 104-8165, Japan
e-mail: chitoshi_akasaka@jpower.co.jp, shigetaka_nakanishi@jpower.co.jp, shigeo_tezuka@jpower.co.jp

2.National Institute of Advanced Industrial Science and Technology
Tsukuba, 305-8567, Japan
e-mail: ishido-t@aist.go.jp

3.Science Applications International Corporation
San Diego, California, 92121, USA
e-mail: John.W.Pritchett@saic.com

ABSTRACT

This paper presents the results of an evaluation of the practicality of using self-potential (SP) monitoring to characterize subsurface changes in a geothermal reservoir caused by field operations. The Onikobe geothermal field has been producing electricity for nearly thirty years. A numerical model of the reservoir had been developed previously, and provides adequate matches to both the natural state conditions and the production history of the field. Recently, the STAR SP postprocessor was applied to this existing reservoir model to calculate temporal changes in SP response at the earth surface. The calculated SP changes are comparable, on the whole, with measured differences between SP surveys performed in 1982 and in 2000. Also, continuous SP measurements were recently carried out at Onikobe for several months, during which the field was shut-in for annual maintenance and then re-started, and temporal SP changes were detected. These changes are in accord with calculated results from the STAR SP postprocessor, and suggest that repeated SP surveys (and/or continuous SP monitoring) could provide useful calibration data for numerical model history-matching studies.

INTRODUCTION

The Onikobe geothermal power station, a 12.5 MWe (gross) single-flash steam turbine plant, has been supplying electricity to the grid for 28 years. Discharge enthalpies and chemical compositions have been monitored for many years, and tracer tests have also been undertaken to help with reservoir management. SP monitoring is expected to be useful in supplementing conventional monitoring methods for reservoir characterization. Among the various mechanisms which can cause SP to appear at the ground surface, the most important appears to be the electrokinetic potentials that arise from underground fluid flow (e.g. Ishido and Pritchett, 1999). Both spatial SP distributions and temporal SP changes may reflect the subsurface flow of geothermal fluid.

Calculation techniques have been devised recently to permit the computation of spatial distributions of, and temporal changes in, SP based on results of numerical reservoir simulations. Comparisons may be made between such calculations and field SP measurements. In this manner, the numerical reservoir model can be refined and improved.

THE ONIKOBE GEOTHERMAL FIELD

The Onikobe Geothermal Field is located in the Backbone Range of northern Honshu Island, Japan,within the Onikobe caldera, which measures approximately 9 km (north-south) by 7 km (east-west) (Figure 1). The Takahinatayama dacite dome is located southeast of the power plant. A triangular 200-meter topographic depression (1.5 km × 0.5 km) has formed on top of the dome, drained by the southward-flowing Ofuka River and the branching Chinoike-Zawa River. This “Katayama Depression” is believed to be a downfaulted block resulting from extensional stresses associated with the formation of the dome. The faults are believed to provide the vertical fluid conduits that charge the Onikobe geothermal reservoir. Extensive areas of surface activity and acid alteration are found along the northern and western sides of the triangular depression (the “Katayama thermal area”).

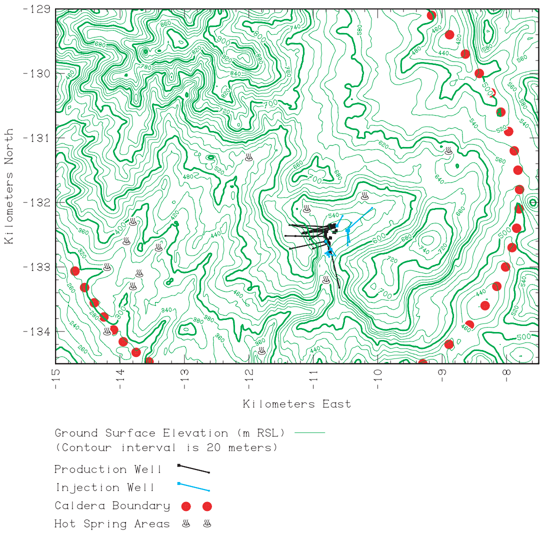

Figure 1. Onikobe geothermal field study area.

The Onikobe wellfield is situated in the Katayama thermal area. Other natural thermal discharge areas surround the Katayama thermal area at radii of 2 to 3 km. The wellfield itself is quite small; the “project area” containing the wellheads and the power station occupies only 0.14 km^2, although the entire area penetrated by the deviated production and injection wells represents around 1 km^2.

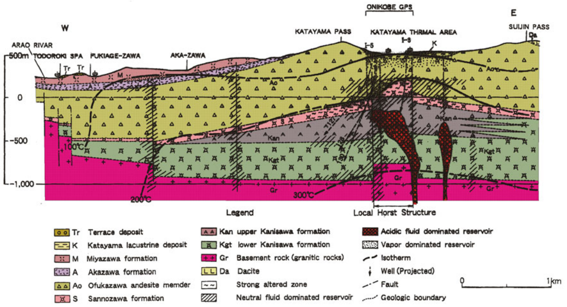

Figure 2. Schematic east-west cross-section of stratigraphy and temperature through the Onikobe geothermal system.

A schematic east-west stratigraphic cross-section is shown in Figure 2. The caldera formed about 2 million years ago. Pleistocene post-caldera volcanism has also taken place. The Pleistocene sequence of pyroclastics, volcanic mudstones, andesites and dacites is underlain by the Miocene Kanisawa Formation (tuff breccias, tuffaceous sediments and andesite lavas), and the Mesozoic granite basement (Klein et al., 1990). Two types of fluids have been withdrawn from production wells – an acidic fluid (pH about 3) and a neutral/alkaline fluid (pH 7 to 8). Klein et al. (1990) and Ajima et al. (1998) discuss the geological and thermal structure and the fluid chemistry.

The fourth Japanese geothermal power facility to be commissioned, Onikobe began producing 9 MWe in March 1975 using an array of shallow production wells. Output was increased to 12.5 MWe in 1976. Unfortunately, this production rate was not sustainable, and by 1980 electricity production had declined below 6 MWe because of insufficient steam. A new deep deviation-drilling program initiated in the early 1980’s raised the field’s generating capacity back to 12.5 MWe as the production and injection wellfields were gradually rearranged during the next few years.

SELF-POTENTIAL MEASUREMENTS

The 1982 SP Survey

A regional self-potential (SP) survey, incorporating the Onikobe geothermal power plant and the surrounding area, was carried out in 1982 by the Geological Survey of Japan (GSJ; now AIST; National Institute of Advanced Industrial Science and Technology), seven years after plant startup in 1975. The purpose of this regional survey was to gain an understanding of the relationships between the earth-surface SP distribution and the underground flow of geothermal fluid. The survey results helped characterize the regional ground water flow, and reflected the local geothermal activity. Therefore, the 1982 survey provides a baseline with which subsequent SP surveys results may be compared to try to identify the effects of field operations.

The 2000 SP Survey

The second SP distribution survey in 2000 was carried out over a smaller area, overlapping that of the earlier 1982 regional survey. Three survey loops were located along exactly the same routes as in the previous survey. Both SP distribution surveys were carried out as similarly as possible. The electrode separation (about 100 m) was the same, and the maximum hard-wire extension length was limited to 500 m or less on either side of the temporal reference point. A few determinations were made at the junctions of two individual wire sections to minimize errors. These careful survey techniques kept “closure errors” below 6 mV for the two shortest survey loops (7.2 km and 4.4 km in length) and 18 mV for the longest loop (13.0km). This type of SP survey measures electrical potential relative to a presumably invariant reference point, so an unstable reference point will make the results harder to interpret. In this survey, relatively stable locations to the northwest of the field were selected as reference points. These are located far from artificial structures, power lines, rivers or roads. The electrical potential near the reference points was assumed to be the same for the two surveys.

The results of the 2000 SP survey are shown in Figure 3. The SP distribution has the following features: (1) alteration zones east of the power station and along the Tashiro river exhibit positive anomalies between zero and several tens of millivolts, (2) the southern part of the survey area has a negative anomaly of –300 mV, and (3) the anomaly around the power station is slightly positive. The regional trends in SP anomalies observed in 2000 are roughly the same as those observed in 1982.

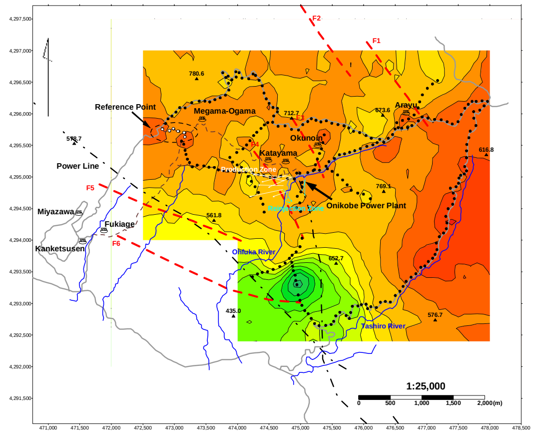

Figure 3. Results of 2000 SP survey. Reference point is in north-western part of survey area. Dots indicate survey points.

To evaluate measurement accuracy, SP profiles along the same survey route for both the 1982 and 2000 surveys are compared in Figure 4. The profiles are nearly identical. On the whole, it does not appear that the regional background changed much between 1982 and 2000, but it does appear that the distant reference point may not have been as stable as had been hoped. On the whole, the surveys are in fairly good agreement, but local small-scale SP changes were observed.

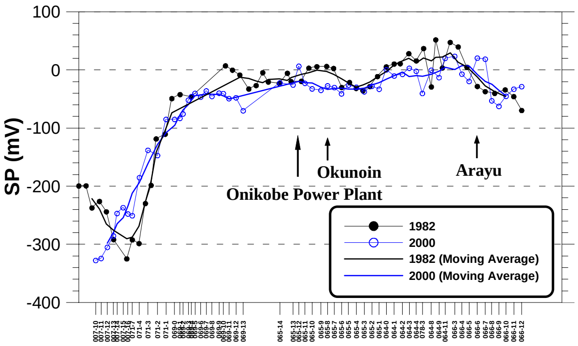

Figure 4. Comparison of SP profile in transverse survey line through central part of survey area between 1982 and 2000. The data in 1982 are shifted for comparing profiles.

The changes in the SP distribution between 1982 and 2000 are shown in Figure 5. The principal features are an SP decrease in the southern part of the survey area and relatively small increases in a central belt extending from northeast to southwest.

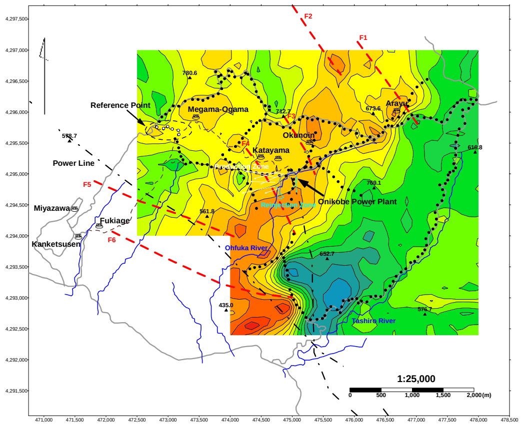

Figure 5. Change in SP distribution from 1982 to 2000. The same northwestern reference point was used for both surveys.

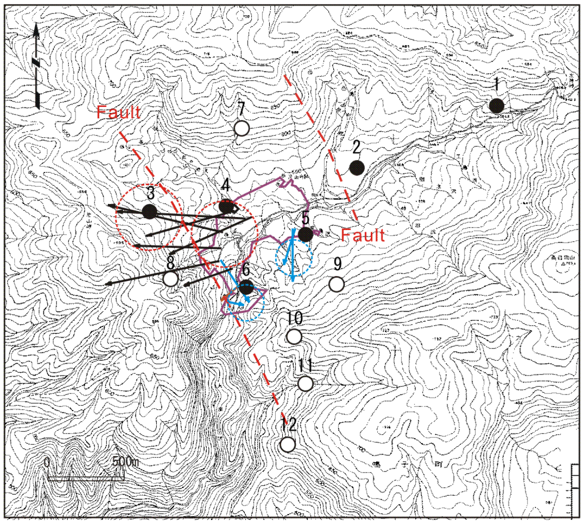

Figure 6. Locations of observation stations for continuous SP monitoring. Solid circles indicate SP monitoring points in 2000. Open circles indicate additional points used for long term SP monitoring in 2001 and 2002. Dashed large red and blue circles indicate the production and injection zones, respectively.

Continuous SP monitoring

Preliminary short term continuous SP monitoring

Continuous SP monitoring was first carried out for several months in 2000 to try to detect electrical potential changes caused by well operations. Six stations were monitored (solid circles in Figure 6) from May to July 2000. This included a period during which all the operating boreholes were shut-in for annual maintenance and then re-started. Two Pb-PbCl non-polarizable electrodes were buried one meter deep at each monitoring station and were hardwire-connected to a multi-channel recording potentiometer. Because the electrical potential measured by the non-polarizable electrode shifts gradually due to electrolyte dilution, a drift correction was applied. The electrodes were checked in a bucket filled with electrolyte before monitoring, then the same check was repeated afterwards. It was assumed that the measured change varied linearly with time. Small high-frequency fluctuations in the measured data were then filtered out numerically. Figure 7 shows the resulting SP change relative to the easternmost observation station (No. 1). Except during a brief recording hiatus, short-term SP variations were observed at all these stations.

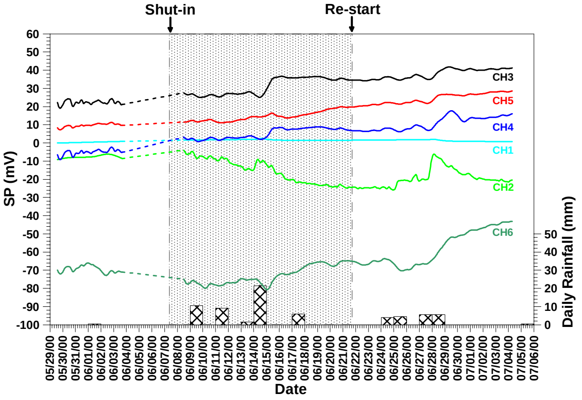

Figure 7. Changes in SP when the boreholes were shut-in for annual maintenance and then re-started. SP is relative to monitoring point No.1 (the westernmost station). Histogram indicates daily rainfall at the Onikobe power station

Long term continuous SP monitoring

Next, long term continuous SP monitoring was carried out for eighteen months, from June 2001 to November 2002. Annual maintenance for the Onikobe geothermal power station normally takes around two weeks, but a main transformer accident occurred in April 2002, which resulted in a three-month shutdown of all the production and injection wells between April 20 and July 16. Continuous SP measurements were conducted in much the same manner as in 2000, but the number of monitoring stations was increased to 12 and the long-term monitoring results were processed by the *"relative SP method"* (Yasukawa et al., 2000) to avoid the uncertainties associated with the reference point of electrical potential. The relative SP method uses the instantaneous average value from all the stations as a time-dependent reference value. A moving time-average was also used to filter out short-period disturbances such as the effects of rainstorms.

Results of this second continuous survey are shown in Figure 8. Data gaps were caused during the winter months by the heavy snow cover, which occasionally caused losses of electrical continuity between the monitoring electrodes and the data logger.

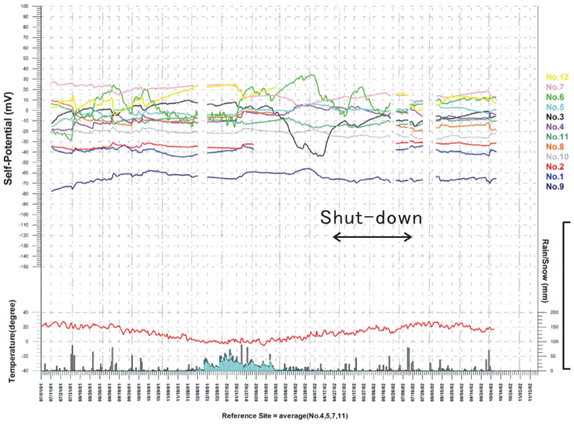

Figure 8. Long term SP change (upper) and precipitation (lower histogram). Lower solid red line indicates air temperature. Blue color in precipitation record denotes snowfall.

Figure 9 shows the SP changes observed between January 2002 and July 2002 (recall that the wells were shut in on April 20). By contrast, Figure 10 shows the SP changes caused by the subsequent system restart, which took place on July 15-16. When the wells were shut in, SP decreased near the production wells and increased in the injection area. When the wells were re-started, the opposite occurred.

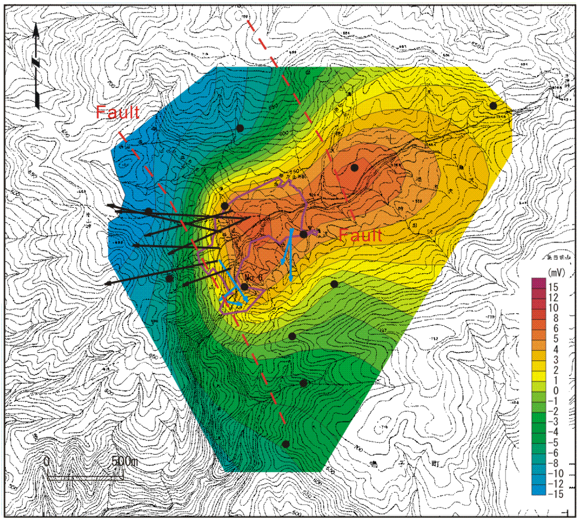

Figure 9. Changes in SP distribution from January 2002 to July 2002, including shut-in.

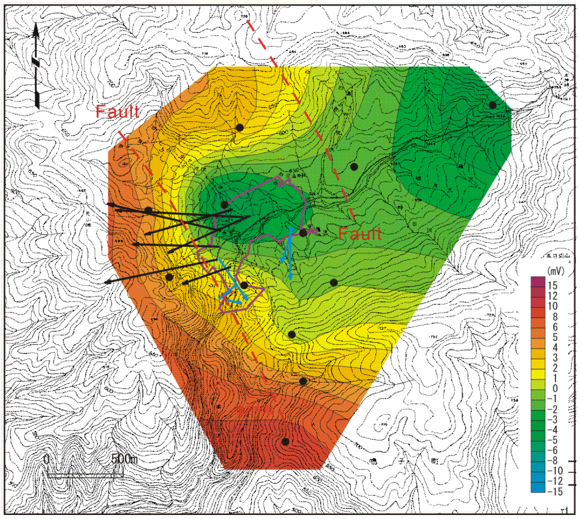

Figure 10. Changes in SP distribution from July 2002 to August, 2002, including re-start.

THE NUMERICAL RESERVOIR MODEL

A mathematical model of the Onikobe geothermal field and the surrounding area had previously been developed by Nakanishi and Iwai (2000) using the STAR geothermal reservoir simulator (Pritchett, 1995). The model exhibits good agreement with the natural state of the system, and history matching (based principally on histories of production well discharge enthalpy) was also successful. This existing numerical model was used to calculate SP response using the STAR *"SP postprocessor"*. This postprocessor (Pritchett, 1995) was developed for the STAR geothermal reservoir simulator to calculate distributions of electrical self-potential along the ground surface, and how they change with time in response to changes in underlying reservoir conditions (Ishido and Pritchett, 1999).

For the numerical reservoir simulation calculations, a computational grid was used consisting of 1406 non-void grid blocks that extends 8 km in the east-west direction and 6.5 km in the north-south direction, and is 2.4 km thick vertically. The northern and eastern vertical grid boundaries were both treated as impermeable and insulated, but constant hydrostatic pressure boundary conditions were imposed on the southern and western vertical grid boundaries. Pressures were also prescribed along the upper surfaces of the topmost grid blocks to permit vertical discharge and recharge of fluid and exchange of reservoir brine with the shallow groundwater system.

The bottom boundary of the computational volume was mainly treated as impermeable with a constant uniform upward conductive heat flux (175 mW/m^2). Mass sources to represent the upwelling flow underlying the Katayama area were distributed in a restricted part of the bottom boundary. The spatial distribution, temperature and strength of these mass sources as well as the permeability distribution throughout the system were used as the main fitting parameters in the natural-state simulation. A fixed uniform upward flux of hot (330°C) liquid water totaling 10 kg/s was finally imposed.

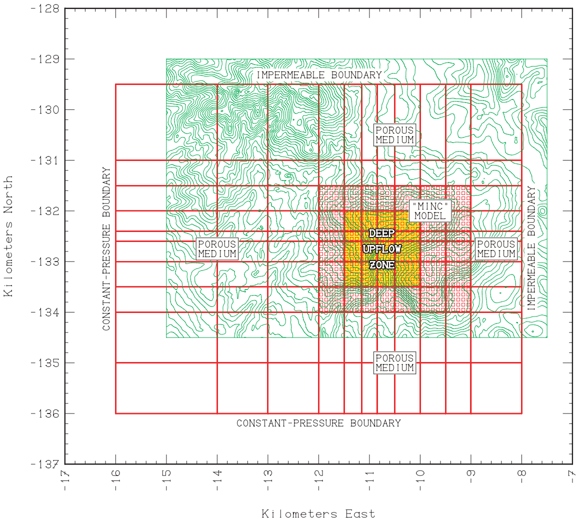

Figure 11. Plan view of the "study area" and the computational grid. Textured area uses "MINC" double-porosity model. Yellow area shows region of deep hot water inflow.

COMPUTED SP CHANGES

In order to calculate the SP distribution, a second grid is superimposed on the STAR grid used to calculate reservoir flow. This "SP grid" extends 18 km × 18 km horizontally and from the ground surface to 3.5 km below sea level. The boundary conditions on the SP grid are (1) zero potential at great distance (laterally and downward) and (2) zero normal potential gradient at the ground surface. Electrical resistivities throughout the entire SP grid volume were assigned to the various major geological formations at Onikobe based on the results of MT and CSAMT surveys. A model for computing the drag current (that is, a model for estimating the zeta-potential and how it will change; the fluid flow pattern is provided by the STAR simulation results) is also required. We used the model developed by Ishido and Mizutani (1981), and it was assumed that the flow paths have unit tortuosity. The "ΔpH" parameter in the Ishido-Mizutani model was taken to be uniform and equal to 4.

The computed natural-state SP distribution is characterized by a regional potential gradient and increases from northeast to southwest. This distribution is strongly influenced by the local topography, which induces regional fluid flows (and the resulting electric currents) from the high ground to the northeast toward the lower-lying regions to the southwest. The general effects of field operations are to progressively cause SP to increase (relative to the natural state) in a limited region surrounding the power station and the wellfield, but also to cause SP to decline at larger radii, particularly to the south.

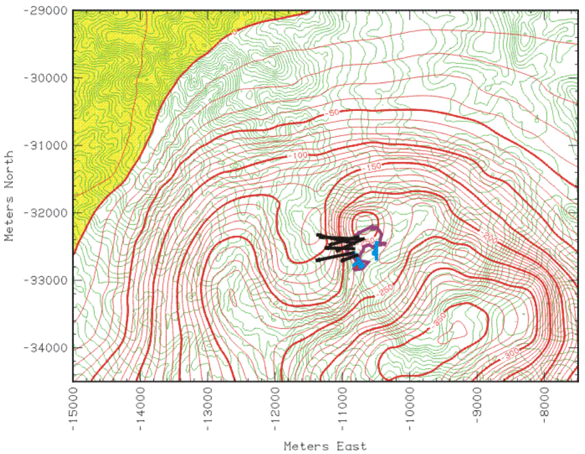

Figure 12. Distribution of computed SP change in study area, 1982-2000.

Figure 12 shows the distribution of computed SP changes (in millivolts) in the Onikobe study area between 1982 and 2000. Computed SP generally decreases during this period, particularly to the southeast of the power station. Computed temporal SP changes during the short term continuous SP monitoring period are shown in Figure 13, relative to the easternmost station (Station 1). Large SP changes are computed at each of the other stations. Note that the results for Station 3 (located directly above the main production zone) differ from the others. Relative to Station 1, Station 3's potential decreased immediately upon wellfield shut-in and then gradually recovered after restart.

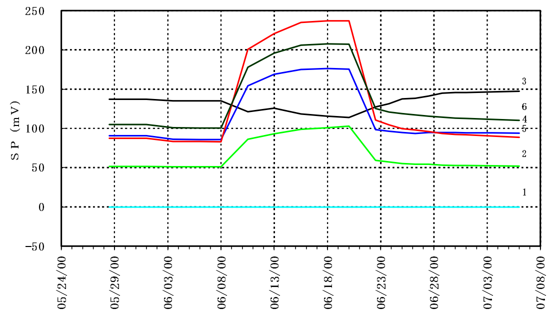

Figure 13. Changes in SP as a function of time during short term preliminary SP monitoring period using 6 stations.

DISCUSSION

Measured changes in the SP distribution from 1982 to 2000 are comparable to computed SP changes. Both distributions indicate substantial SP decreases of comparable magnitudes to the southeast of the power station, and both feature a northeast-southwest band characterized by slightly increasing relative SP near the power station. The computed results are thus in reasonable agreement with measurements, supporting the underlying mathematical reservoir model.

The effects of wellfield shutdown and restart upon SP, as measured in the preliminary monitoring experiments in 2000, are difficult to understand. Results from the longer-term monitoring period in 2001-2002 are much more reasonable, and are moreover in agreement with the calculated SP changes. In particular, both observations and calculations exhibit relative SP decreases above the production area upon shut-in owing to the cessation of the "drag current" flowing towards the production well feed-points.

In the measurements, noise was introduced by both electrode drift and rainfall (or snowfall). As noted above, electrode drift was corrected using before-and-after calibration measurements and assuming linear drift. The effects of precipitation were minimized by simply ignoring measurements acquired within a few days after a storm, and also by applying low-pass filtering to the continuous monitoring data.

CONCLUSIONS

Observed SP changes between 1982 and 2000 include SP increases of several tens of millivolts centrally near the power station including the production and injection wellfields, and SP decreases to the southeast of 150 to 200 millivolts. These trends are consisted with computed results from the SP postprocessor based upon the numerical reservoir model. Repeat SP surveys can therefore be useful in verifying such models. Measured temporal changes in SP caused by shut-in and re-start have the same trends as computed results, although differences are present in detail. This suggests that the numerical model could be improved, particularly as regards its short-term response characteristics. These studies indicate that SP monitoring can be useful to help characterize geothermal systems, and is a cost-effective approach to monitoring the behavior of geothermal reservoirs during production operations.

ACKNOWLEDGMENTS

The authors wish to thank the management of the Electric Power Development Company, Ltd. (EPDC) for the permission to publish this paper. We would also like to thank H. Muratake and H. Oshima of Kaihatsu Computing Service Center, Ltd. (KCC) for their generous help with the computing aspects of the study, and K. Yokoi and T. Deguchi of Nittetsu Mining Consultants Company, Ltd. for supporting the SP measurements. The STAR SP postprocessor implementation on the PC was developed under the New Energy and Industrial technology Development Organization (NEDO) project “Development of Technology for Reservoir Mass and Heat Flow Characterization”.

REFERENCES

Ajima, S., Todaka, N., and Muratake, H. (1998), “An interpretation of smectite precipitation in production wells caused by the mixing of different geothermal fluids”, *Proc. Twenty-third Workshop on Geothermal Reservoir Engineering,* Stanford Univ., 264-269.

Ishido, T. and Mizutani, H. (1981), “Experimental and Theoretical Basis of Electrokinetic Phenomena in Rock-water Systems and Its Applications to Geophysics,” *Journal of Geophysical Research*, **86**, 1763-1775.

Ishido, T. and Pritchett, J. W. (1999), “Numerical Simulation of Electrokinetic Potentials Associated with Subsurface Fluid Flow,” *Journal of Geophysical Research*, **104**, B7, 15,247-15,259.

Klein, C. W., McNitt, J. R., Sanyal, S. K., Abe, M. and Nakanishi, S. (1990), “Corrosion vs. Temperature: Field Development Options at Onikobe Geothermal Field, Miyagi Prefecture, Japan,” *Trans. Geotherm. Resour. Counc.*, **14**, Part II, 1493-1499.

Nakanishi, S. and Iwai, N. (2000), “Reservoir Simulation Study of the Onikobe Geothermal Field, Japan,” *Proc. World Geothermal Congress 2000, Japan*, 2159-2164.

Pritchett, J. W. (1995), “STAR: A Geothermal Reservoir Simulation System,” *Proc. World Geothermal Congress 1995, Florence*, 2959-2963.

Pritchett, J. W. (1999), *“STAR User’s Manual, Revision F”*, Maxwell Technologies Report No. SSS-TR-92-13366.

Yasukawa, K., Suzuki, I. and Ishido, T. (2000), “Reservoir Monitoring by Relative Self-Potential Observations at the Nigorikawa Basin, Hokkaido, Japan,” *Trans. Geotherm. Resour. Counc.*, **25**, 705-710.