Self-Potential Monitoring at the Sumikawa Geothermal Field, Akita, Japan

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ABSTRACT

In addition to electrokinetic coupling, self-potential (SP) anomalies may be generated by various other mechanisms such as thermoelectric coupling, electrochemical diffusion potential, etc. In particular, SP anomalies of negative polarity, which are frequently observed near wells, appear to be caused by an underground electrochemical mechanism similar to a galvanic cell known as a geobattery: the metallic well casing acts as a vertical electronic conductor connecting regions of differing redox potential. Electrons flow upward though the casing from a deeper reducing environment to a shallower oxidizing environment, and simultaneously a compensating vertical flow of ions is induced in the surrounding formation to maintain charge neutrality. Ishido and Pritchett (2011) extended the SP postprocessor (Ishido and Pritchett, 1999) to incorporate the above geobattery mechanism in addition to electrokinetic coupling. Here, we report the results of self-potential monitoring at the Sumikawa field since the early 1980s (which began before the startup of the Sumikawa geothermal power station in 1995) and present interpretations of the SP monitoring results based upon reservoir simulations and successive SP postprocessor calculations.

1. INTRODUCTION

The self-potential (SP) method has attracted increasing interest in geothermal prospecting. Among the various mechanisms which can cause SP in geothermal areas, the most important appear to be streaming potentials (e.g., Zohdy et al., 1973; Corwin and Hoover, 1979; Ishido and Mizutani, 1981). Electrokinetic effects are almost certainly responsible for the production-induced changes in SP which take place after a field is developed (Ishido and Pritchett, 1996). Repetitive SP surveying of geothermal fields during exploitation represents a promising tool for geothermal field monitoring and resource management.

When a sink or source of fluid is present within a reservoir as a result of production or reinjection of geothermal fluids, a surface electric potential anomaly can be produced through electrokinetic coupling if the following conditions are satisfied. First, there must be a boundary separating regions of differing streaming potential coefficient (C); second, there must be a nonzero component of pressure gradient parallel to this boundary (Fitterman, 1978). A temperature boundary, a boundary between regions of different pore water chemistry, and/or a contact of different rock formations are the most likely causes for discontinuities in the value of C in a geothermal reservoir (Ishido et al., 1989).

During the past two decades, numerical modeling of SP generation has been undertaken in geothermal and hydrological studies (e.g., Sill, 1983; Yasukawa et al., 1993; Ishido and Pritchett, 1996). The method proposed by Ishido and Pritchett (1999) applies the so-called "EKP postprocessor" to the results of an unsteady thermohydraulic reservoir simulation. First, it calculates the distributions of pertinent parameters such as the electrokinetic coupling coefficient, the electrical conductivity, and the drag current density using the results from the reservoir simulation. Next, the postprocessor calculates the electric potential distribution by solving the Poisson's equation within a finite-difference grid with appropriate boundary conditions. This method was applied to reproduce SP changes induced by fluid production and re-injection observed at geothermal fields in Japan; the Mori field (Ishido and Pritchett, 1999), the Kirishima field (NEDO, 2003a) and the Okuaizu field (Nishi and Ishido, 2012) so far.

Care must be exercised in interpreting SP data from areas where fluid production is taking place, in particular noise associated with newly drilled wells, deployed pipelines, and so forth need to be evaluated. At the Sumikawa field in Japan, SP surveys were carried out twice before the startup of the geothermal power station in 1995 and again three times afterwards (Matsushima et al., 2000). Unfortunately, no data free from "artificial" noise are available except that from the first survey in 1983. Negative potentials of up to several hundred millivolts are present near metallic artifacts such as well casings and pipelines. The pipelines, which were deployed after 1983 along the principal survey lines used in the 1983 survey, are connected to the wellheads and are in electrical contact with the ground surface at various locations. Continuous SP measurements near the wellheads and pipelines show that temporal potential changes correspond to temporal temperature variations near the surfaces of the metallic structures, which could be explained by a simple "redox" model (Ishido, 2008).

In this paper, first an outline of repeated and continuous SP measurements carried out at the Sumikawa field is given, and then the SP postprocessor calculations based upon reservoir simulation results are described. Finally the results from the extended SP postprocessor (which incorporates the geobattery mechanism, Ishido et al., 2013) regarding the negative potential behavior observed near the well casings and pipelines are discussed.

2. SELF-POTENTIAL DATA AT THE SUMIKAWA FIELD

2.1 SP distribution observed by repeat surveys

Mt. Yake, located in the Sengan geothermal area of northern Honshu, is an active volcano and has many thermal manifestations such as fumaroles, hot springs and alteration zones. Under a joint program, the Geological Survey of Japan (GSJ) and NEDO conducted geological, geochemical, and geophysical surveys and also conducted an exploratory drilling program in the Sengan geothermal area. SP surveys in the Mt, Yake area were carried out by GSJ starting in 1979. Exploration efforts were also undertaken by Mitsubishi Material Corporation (MMC; Mitsubishi Metal Corporation up to 1990), who has been operating a 9.5 MW geothermal power plant at Ohnuma since 1974 and a 50 MW geothermal power plant at Sumikawa since 1995.

Surface rocks in the area shown in Figure 1 are mostly andesitic lavas from Mt. Yake, 1336 mASL in elevation. The elevations of the fumaroles and hot springs shown in Figure 1 are generally from 700 to l100 m except for the fumaroles near the volcano summit and for the Zenikawa bicarbonate hot springs to the north (520 m). The most remarkable feature of the thermal waters of the area is their compositional diversity. Waters discharged from production wells in the Ohnuma and Sumikawa fields have neutral pH and total dissolved salt contents of about 2000 ppm on the average.

SP measurements were made using copper-copper sulfate (or silver-silver chloride) nonpolarizing electrodes and a high-impedance voltmeter. For each survey line, the maximum wire length (from a fixed base electrode) and the data sampling intervals were 2000 and 100 meters respectively. In compiling the contour map (Figure 1) showing the distribution of SP in the Mt. Yake area, the potentials measured along the various survey lines were tied to a common ground reference and then subjected to a smoothing process. Closure offsets were relatively small: for example, a 48.7 km loop traverse was closed with an error of 5.0 mV.

As shown in Figure 1, anomalies of positive polarity appear in three areas: on the northern and southeastern flanks of Mt. Yake, and at the volcano summit. The positive anomaly to the north of Mt. Yake overlies the Sumikawa field. The SP distribution in the Sumikawa area is also shown in Figure 2 (left). As shown in Figure 2 (right), the positive SP over the central area disappeared in 1997, two years after the startup of the Sumikawa geothermal power plant in 1995.

To investigate causes of the positive SP disappearance, we measured the SP profile along a survey line perpendicular to the main road used for the SP surveys, along which a steel pipeline connected to injection wells is deployed on the ground surface. As seen in Figure 3, the negative SP is thought to be produced by a current source located at the pipeline. As discussed later, this current source is thought to be generated by "geobattery" mechanism. If we exclude this artificial SP, the background SP in the central area of the Sumikawa field is thought to still be as high as about +100 mV.
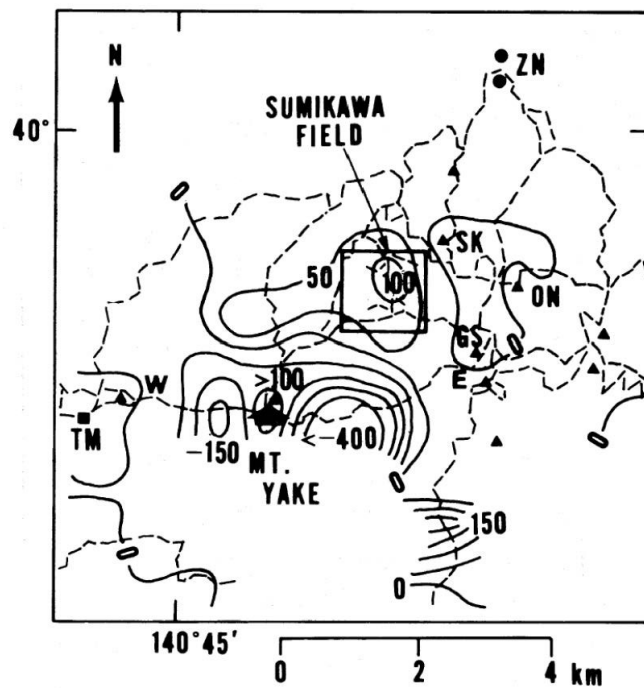

Figure 1: Self-potential distribution in the Mt. Yake area in 1983. Contour interval is 50 mV. Survey lines are shown by broken lines. Areas with fumaroles and/or steam-heated sulfate type springs are shown by triangles (SK, Sumikawa; ON, Ohnuma; GS, Goshogake). Areas with chloride-bicarbonate type thermal water discharge are shown by solid circles (ZN, Zenikawa). Tamagawa (TM) hot spring area is shown by a solid square. (after Ishido et al., 1989)
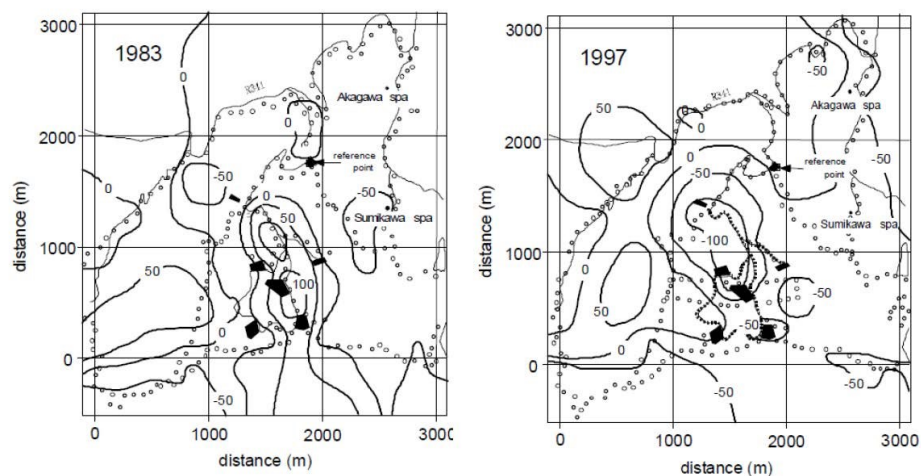
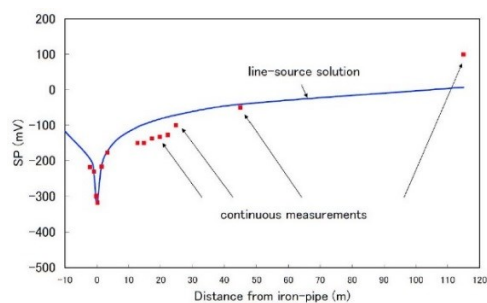**Figure 2: SP distribution in the Sumikawa field in 1983 (left) and in 1997 (right). (after Matsushima et al., 2000).**

Figure 3: SP profile along a survey line perpendicular to a steel pipeline deployed on the ground surface.

2.2 Temporal SP variation recorded by continuous measurements

In order to investigate behavior of the negative SP near the pipeline and to detect SP changes associated with field-wide shut-ins of production and injection wells, we carried out continuous SP measurements using four Ag/AgCl electrodes located 5 m, 10 m, 30 m and 100 m away from the pipeline. As shown in Figure 4, the negative SP near the pipeline exhibits annual fluctuations with the magnitude increasing and decreasing in summer and winter, respectively. This feature is discussed later on the basis of the calculations of the extended SP postprocessor which incorporates the "geobattery" mechanism. As seen in Figure 4, the SP of the electrode located 100 m away from the pipeline is quite stable between 2005 and 2014 (data for 2010 to 2014 are not shown here).
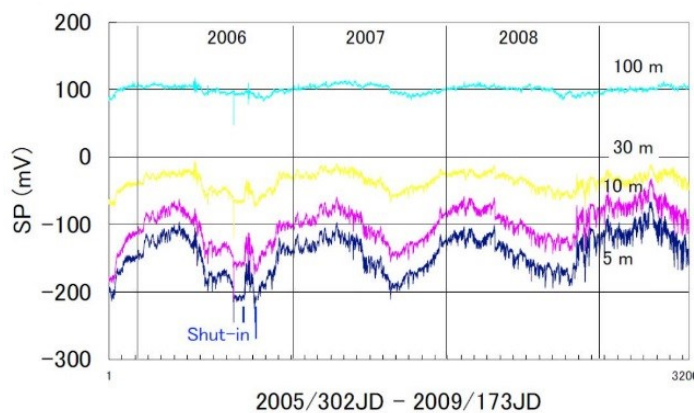

Figure 4: Continuous SP records for electrodes located 5m, 10m, 30m and 100m away from the pipeline.

3. NUMERICAL SIMULATION OF SELF-POTENTIAL

3.1 Calculation of Electrokinetic Potential Based Upon Reservoir Model

We applied the SP postprocessor to a reservoir model which was built through natural-state simulations and calibrated against various reservoir engineering data through history-matching studies (Figure 5, NEDO, 2003b). The STAR simulator (Pritchett, 1995; 2002) was used to perform a 50-year forecast of the consequences of production, starting from the natural-states calculated for the *"POROUS"* model as the initial conditions. All boundary conditions are the same as those used to calculate the natural-state. As for the rock properties, they are represented by *"MINC"* media with impermeable matrix. The calculations were carried out by using STAR's capability to treat "geothermal power systems", which allows us to allocate fluid production rate to various wells so as to maintain a given power generation scenario.

Figure 6 shows the calculated SP distribution under the natural state, and Figure 7 shows the SP distribution in 2003 and 2014, which were calculated by applying the SP postprocessor to the reservoir simulation results. The calculated results indicate that the SP distribution did not change much in the central area of the Sumikawa field during the eleven years between 2003 and 2014, which is consistent with our continuous and repeat SP measurements. As seen in Figure 8, substantial changes in mass flow, etc. took place in the underlying reservoir region after fluid production started, but the associated changes in potential did not reach the earth surface due to the presence of an intervening conductive layer corresponding to the caprock.

Figure 9 shows the SP distribution in 2003 and 2014, which were calculated based upon a reservoir model which assumes the reservoir rocks being represented by *"MINC"* media with permeable matrix, the permeability and porosity of which are assumed as 10^{-18} m^2 and 0.01, respectively. In this case, owing to the contribution of drag current within the matrix region (Ishido and Pritchett, 2003), quite large changes during the eleven years between 2003 and 2014 are predicted. This is inconsistent with the observations. Our observations are more consistent with the original assumption: the "impermeable matrix" representation used in the 2002 model (NEDO, 2003b).
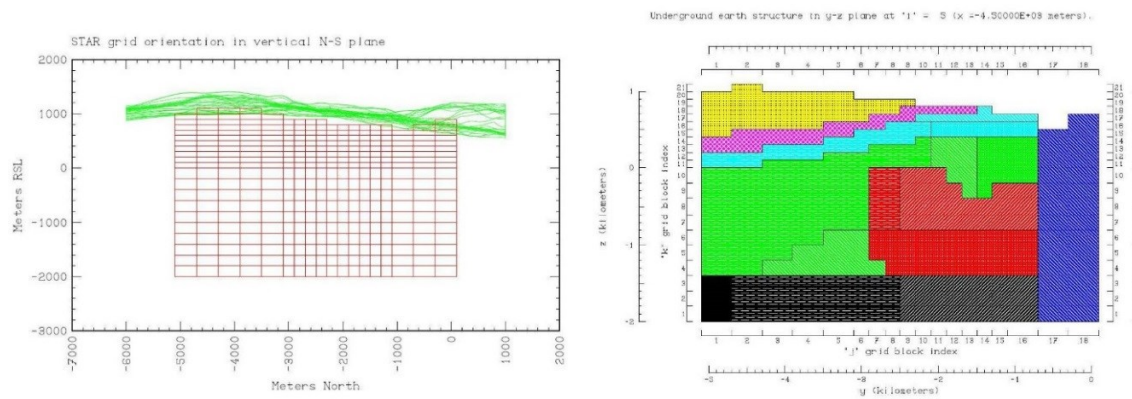

Figure 5: STAR computational grid (left) and earth structure (right) used for Sumikawa modelling study – north-south vertical plane.
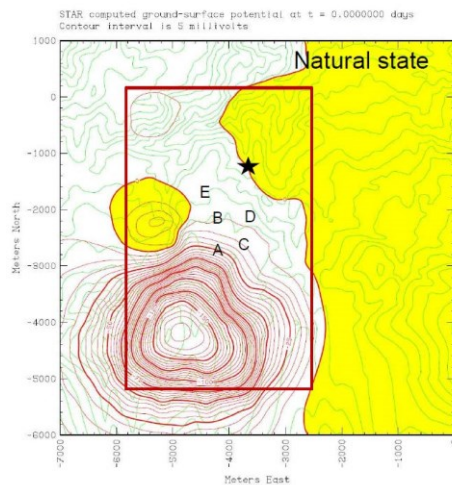

Figure 6: Calculated SP distribution under the natural state. "A", "B", "C", "D" and "E" indicate the location of well sites, and the "star" indicates the location of the reference electrode.
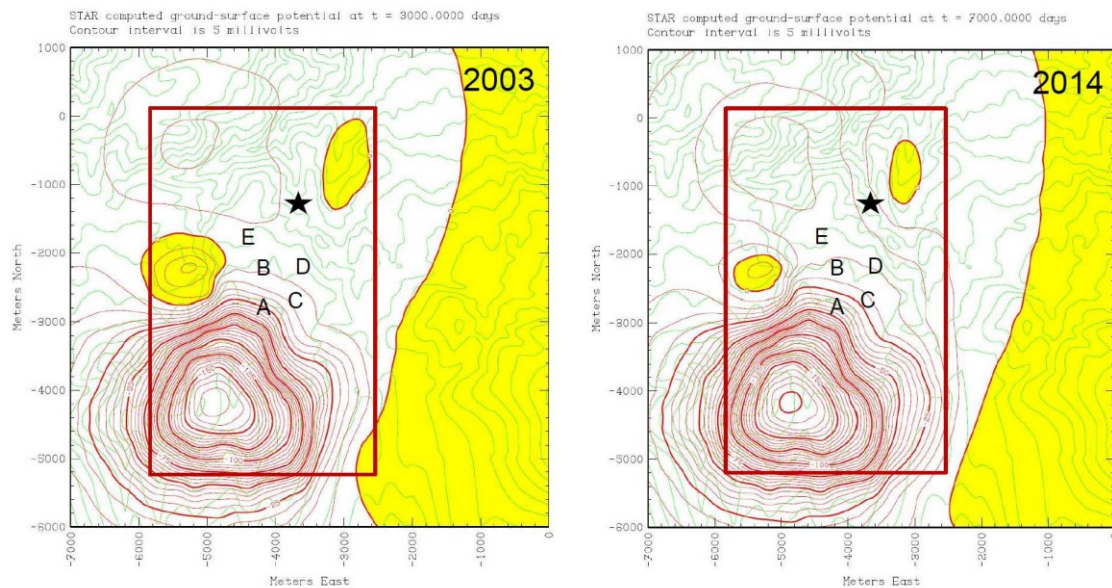
Figure 7: Calculated SP distribution during exploitation - eight years (left) and nineteen years (right) after the startup of the Sumikawa geothermal power plant in 1995. In the reservoir simulation, all rocks are represented by MINC media with impermeable matrix. The results shown here are consistent with the observations.
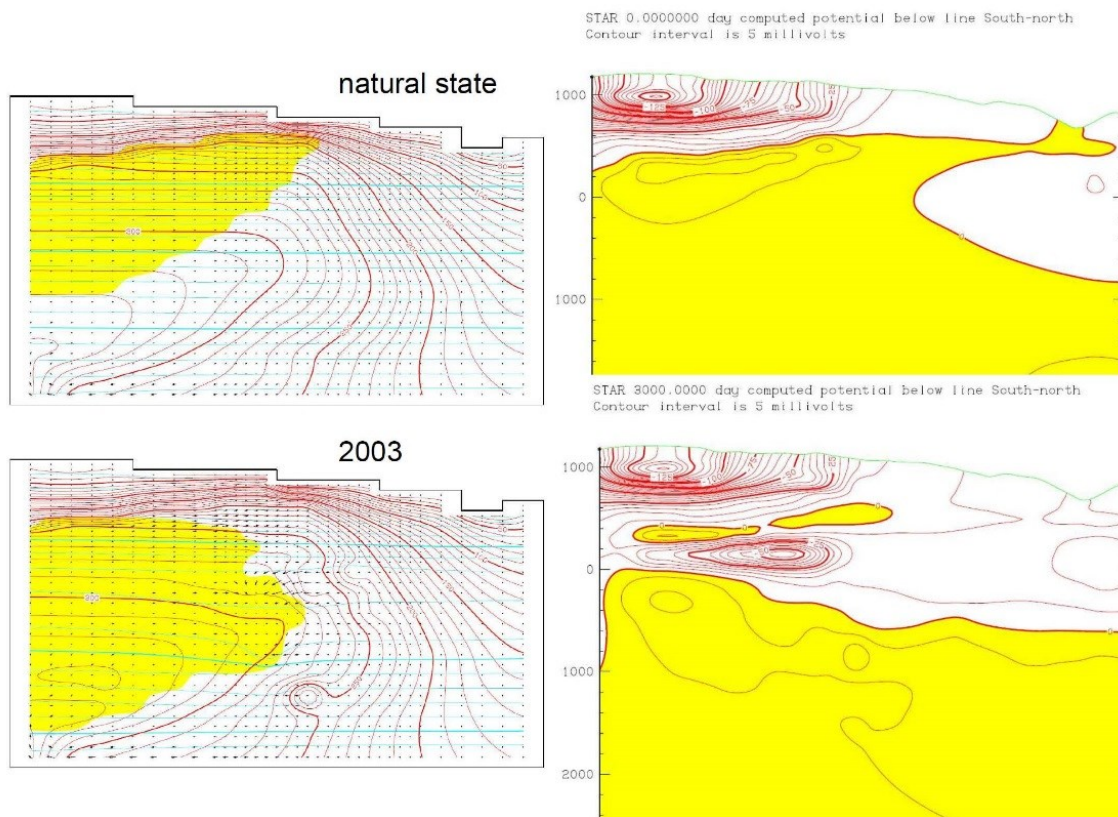

Figure 8: Pressure, temperature and steam distributions (left) and potential distributions (right) along a vertical plane, for natural state (upper) and exploitation state in 2003 (lower).
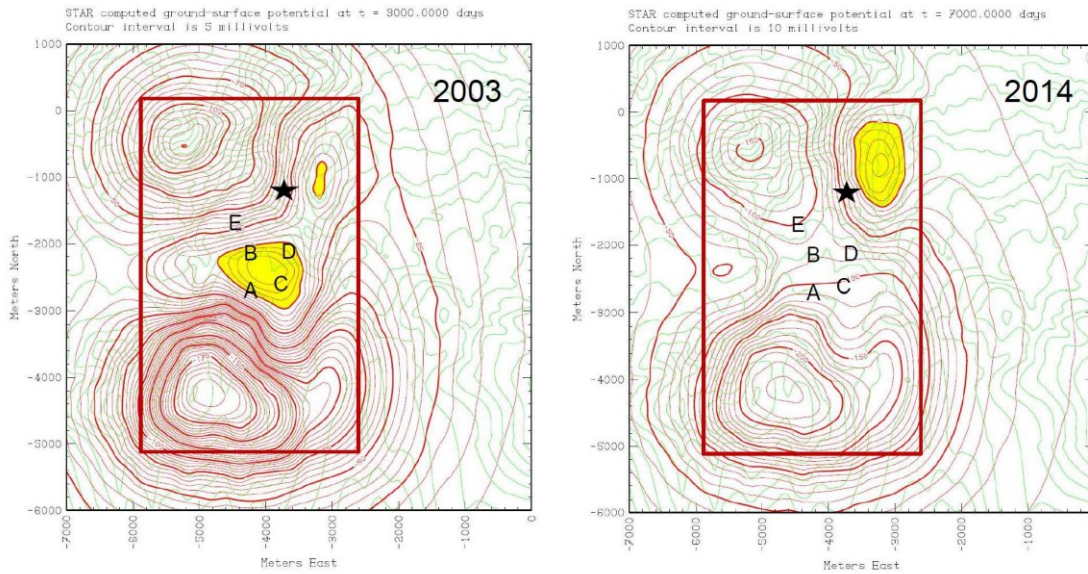
Ishido et al.

Figure 9: Calculated SP distribution under the exploitation condition. Eight years (left) and nineteen years (right) after the startup of the Sumikawa geothermal power plant in 1995. In the reservoir simulation, the reservoir rocks are represented by MINC media with permeable matrix. The results shown here are inconsistent with the observations.

3.2 Calculation of Negative Potentials Associated With "Geobatteries"

In order to take the geobattery mechanism into account, we must provide additional input parameters such as the geometries of electronic conductors (metallic well casings, etc.) and electrochemical parameters concerning the cathodic and anodic reactions to calculate the Redox potential (E_H) and the exchange current density (I_0) distributions along the metallic artifacts from the reservoir conditions such as temperature, pH, P_{O2} and concentrations of ions such as Fe^{2+} and Fe^{3+}. The initial distributions of E_H (calculated using a procedure similar to that of Bigalke and Grabner, 1997) and the electronic conductor potential (E_m) and SP, which are obtained by solving the fundamental equations simultaneously, are shown in Figure 10 (see Ishido et al., 2013 for a description of the extended SP postprocessor.)

An example of outputs of the extended SP postprocessor is shown in Figure 10 for a case of CO_2 injection calculation. After one year of CO_2 injection E_H increases by ~1.3 V (and I_0 increases by more than two orders of magnitude) at the injection depth. This is brought about by pH reduction of more than 3 due to CO_2 dissolution, which is calculated by a pH model incorporated in the postprocessor, and by a tiny increase in P_{O2} (~10^{-10} Pa) assumed to accompany the injected CO_2. As a result, E_m increases by ~1.1 V and SP centered on the wellhead increases from ~ -30 to ~0 mV.

Figures 11 and 12 show SP distributions near the steel pipeline calculated by applying the extended SP postprocessor to the Sumikawa reservoir model mentioned above. The observed SP changes shown in Figure 4 are roughly reproduced in the calculation, in which the electrical resistivity of near surface soil is assumed to be 1,000 Ωm and 100,000 Ωm in summer and winter, respectively.

4. CONCLUSIONS

We carried out continuous SP measurements to clarify the causes of negative SP anomaly near a steel pipeline deployed on the ground surface, which is connected to the wellheads of injection wells of the Sumikawa geothermal power plant, between 2005 and 2014. By applying the extended SP postprocessor, which incorporates the "geobattery" mechanism in addition to electrokinetic coupling, to the reservoir model (NEDO, 2003b), it is revealed that the observed peculiar behavior of the negative anomaly is explained by changes in the exchange current (associated with the "geobattery") between the pipeline and the ground surface due to changes in near surface resistivity.

Excluding the local negative SP anomaly near the pipeline, the SP distribution in the central area of the Sumikawa field does not change much during eighteen years of fluid production and reinjection. This observation is well reproduced in the SP postprocessor calculation of electrokinetic potential based upon the reservoir model (NEDO, 2003b).
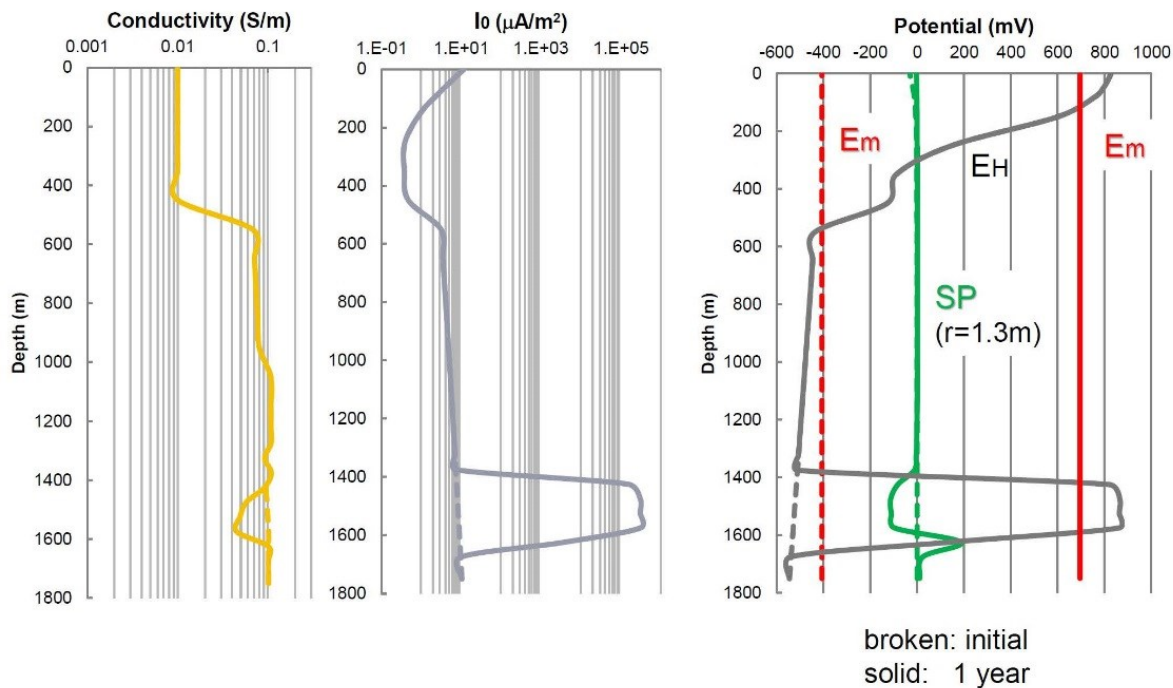
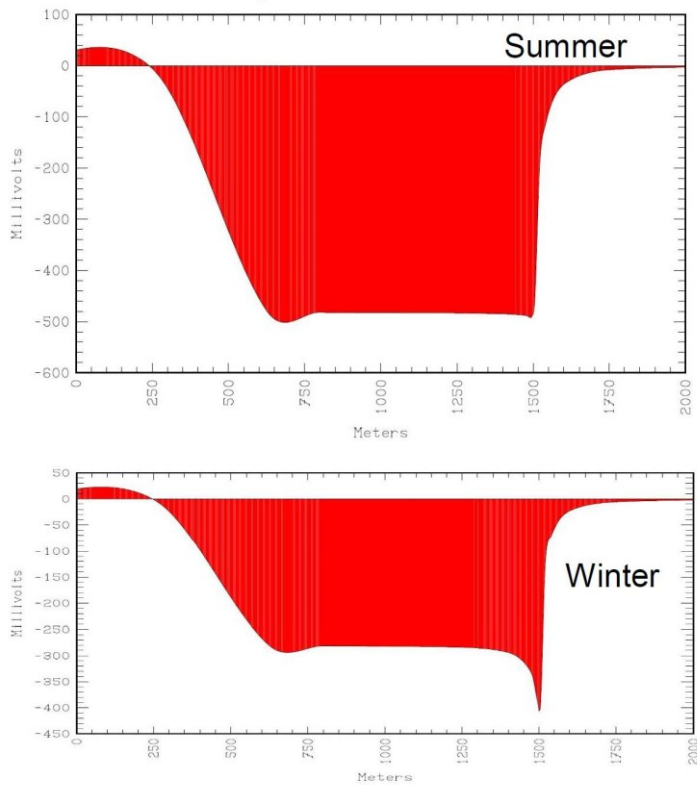Figure 10: An example of outputs of the extended SP postprocessor to incorporate "geobattery" mechanism.

Figure 11: Calculated SP distribution along the steel pipeline in the Sumikawa field. In "winter" case, the soil resistivity near the ground surface is assumed to be very high corresponding to freezing.
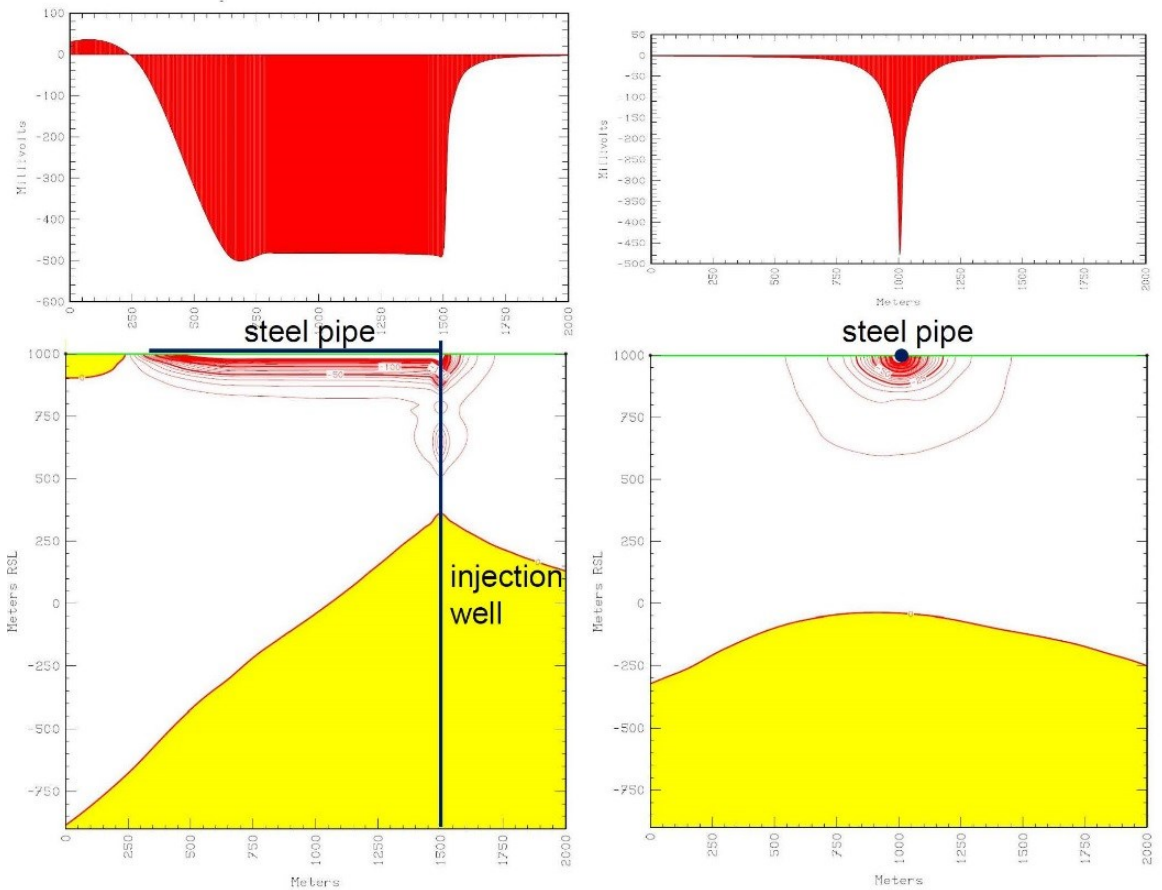
Ishido et al.

Figure 12: Calculated SP distribution along the steel pipeline (left) and along a line perpendicular to the pipeline (right) in the Sumikawa field. Vertical sections of potential distribution are shown in the lower panels.

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