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THE ELECTROKINETIC MECHANISM OF HYDROTHERMAL-CIRCULATION-RELATED AND PRODUCTION-INDUCED SELF-POTENTIALS

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ABSTRACT

Self-potential (SP) surveys were carried out on a number of geothermal areas in Japan during the last decade. In most cases SP anomalies of positive polarity are found to overlie high temperature upflow zones. Streaming potential generated by hydrothermal circulation (Ishido, 1981) is considered to be the most likely cause of the observed positive anomalies. Repeated surveys conducted on the Nigorikawa caldera in Japan detected a change in SP induced by production of geothermal fluids. The observed change is dipolar in waveform and can also be attributed to an electrokinetic mechanism.

INTRODUCTION

Self-potential (SP) anomalies of widely varing amplitude, polarity, and spatial extent have been reported from several geothermal areas (Zohdy et al., 1973; Zablocki, 1976; Anderson and Johnson, 1976; Corwin and Hoover, 1979). The various mechanisms involved in producing these surface potentials have not been positively identified; however, an electrokinetic process related to the upward movement of pore fluids is believed to have caused the anomalies of positive polarity observed in Hawaii (Zablocki, 1976), Yellowstone (Zohdy et al., 1973), and Long Valley (Anderson and Johnson, 1976).

Quantitative modeling of the potential generating mechanism for hydrothermal circulation was done by Ishido (1981). His modeling is based on realistic values of the electrokinetic coupling coefficients for crustal rock-water systems estimated from experimental results (Ishido and Mizutani, 1981; Ishido et al., 1983). In this paper, the modeling presented by Ishido (1981) will be explained briefly, and some examples from recent self-potential surveys done in Japan will be given. Following the discussion of the SP anomalies under natural state conditions, a change in SP induced by production of geothermal fluids will be described.

STREAMING POTENTIAL ASSOCIATED WITH HYDROTHERMAL CIRCULATION

The flow of a fluid through a porous medium may generate an electric potential gradient (called the electrokinetic or streaming potential) along the flow path by the interaction of the moving pore fluid with the electrical double layer at the pore surface, a process known as electrokinetic coupling. The phenomenological equations describing electrokinetic coupling in a porous medium are given by Ishido and Mizutani (1981) on the basis of the capillary model:

$$\vec{I} = -\eta t^{-2}\sigma\cdot\nabla\phi \quad + \eta t^{-2}(\varepsilon\zeta/\mu)(\nabla P - \rho\vec{g}) \qquad (1)$$

$$\vec{J} = \eta t^{-2}(\varepsilon\zeta/\mu)\nabla\phi - (k/\mu)(\nabla P - \rho\vec{g}) \qquad (2)$$

where $\vec{I}$ is the electric current density, $\vec{J}$ is the fluid volume flow flux; ϕ is the electric potential, P is the pore pressure; $\vec{g}$ is the acceleration of gravity; ρ, ε, and μ are the density, dielectric constant, and viscosity of the pore fluid, respectively; η, t, and k are the porosity, tortuosity, and permeability of the porous medium, respectively; $\sigma = \sigma_f + m^{-1}\sigma_s$ (σ_f, pore fluid electrical conductivity; σ_s, surface electrical conductivity; and m, hydraulic radius); and ζ is the zeta potential, the potential across the electrical double layer.

Neglecting the first term in the right-hand side of (2)(this term can be neglected safely for geologic materials) and substituting (2) into (1) yields:

$$\vec{I} = -\eta t^{-2}\sigma\{\nabla\phi + C(\mu/k)\vec{J}\} \qquad (3)$$

where C ($= \varepsilon\zeta/\sigma\mu$) is called the streaming potential coefficient. If C is negative (positive), the positive (negative) charge is carried by the fluid flow $\vec{J}$. In the absence of current sources, $\nabla\vec{I} = 0$; and for homogeneous regions, by using (3):

$$\nabla^2\phi = -C(\mu/k)\nabla\vec{J} \qquad (4)$$

Considering thermally driven convection in single-phase (liquid) systems, $\nabla\vec{J} = 0$(Boussinesq approximation), we get,

$$\nabla^2\phi = 0 \qquad (5)$$

Sources for ϕ therefore can only occur at boundaries. Continuity of normal current flow requires

$$\hat{n}\cdot\vec{I}_1 = \hat{n}\cdot\vec{I}_2 \qquad (6)$$

where $\hat{n}$ is the unit vector normal to the boundary.

When a hydrothermal convection cell is confined to depth and no fluid flow intersects the surface, no surface electric potential anomaly will appear for a uniform half space, since the solution of (5) without any sources for ϕ must be zero throughout the half space. This is not the case, however, for inhomogeneous media (where there are boundaries between regions of differing physical properties such as C) since electric charge can be accumulated by fluid flow at the boundaries.

The streaming potential coefficient C in the earth is expected to be inhomogeneous rather than homogeneous. Figure 1 shows that C for the crustal rock-water system is very sensitive to the chemical composition of the pore water and to the temperature of the system (Ishido et al., 1983). (The polarity of C's shown in figure 1 is negative except for those shown by broken lines.) This implies that C is inhomogeneous in a hydrothermal convection cell, in which there is a large temperature change.

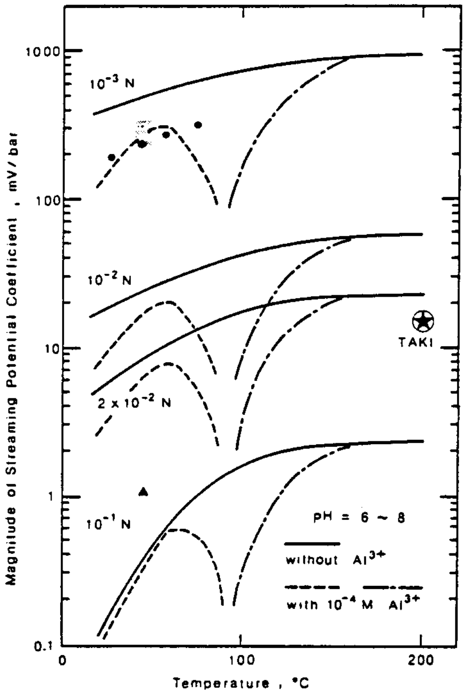

Fig. 1 The magnitudes of streaming potential coefficients of crustal rock-water systems as a function of temperature in 10^{-3}, 10^{-2}, 2×10^{-2} and 10^{-1} mol/l NaCl electrolytes (liquid phase) with and without 10^{-4} mol/l Al^{3+}. Also shown is the value of C obtained in the Takinoue geothermal field (TAKI). (After Ishido et al., 1983.)

By using the values of C estimated from the experiments (Ishido and Mizutani, 1981; Ishido et al., 1983), Ishido (1981) did quantitative modeling of electric potentials generated by hydrothermal circulation through a electrokinetic coupling. Equation (5) was solved numerically with boundary condition (6). In one of the models (Figure 2), a half space below the surface was divided into two regions: the first characterized by temperature above 150°C and the other characterized by lower temperatures. Physical properties of the higher and lower temperature regions are assumed to be those at 200° and 100°C, respectively. Considering the crustal rock-water system, the water chemistry of which is: pH = 7, 0.02 mol/l NaCl, 10^{-5} mol/l Al^{3+}, Ishido (1981) estimated the values of C as -35 and 0 mV/bar for the higher and lower temperature regions respectively (see also Ishido and Mizutani, 1981). As shown in figure 2, positive electric potential appears around the portion of the higher-lower temperature boundary intersected by the outward fluid flow from the higher temperature region.

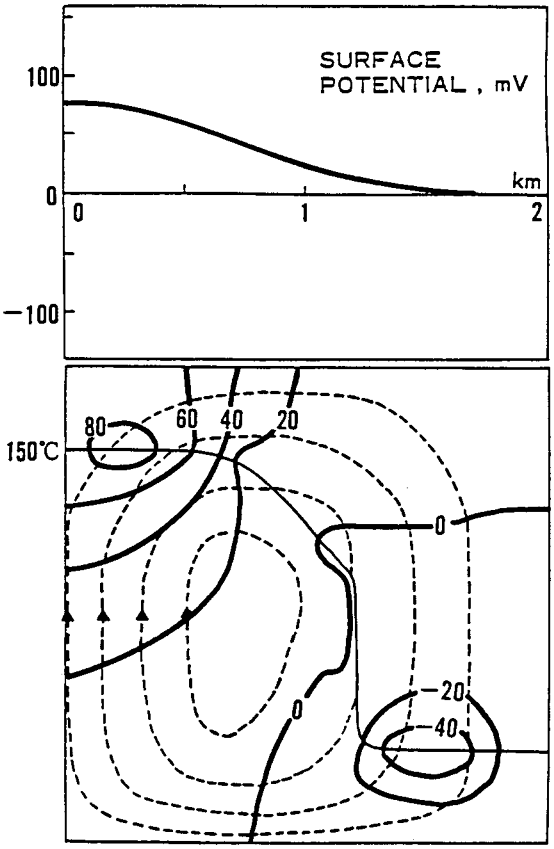

Fig. 2 The lower diagram shows the electric potential distribution (solid lines, in mV) generated by hydrothermal circulation (stream lines are shown by broken lines). The whole region is 2x2 Km^2 and divided into two regions by 150 °C isotherm. The upper diagram shows the SP distribution on the earth's surface. (after Ishido, 1981)

The accumulation of positive charge at this portion of the boundary is caused by fluid flow carrying positive charge ($C < 0$) and no charge ($C = 0$) in the higher and the lower temperature regions, respectively.

Ishido (1981) has shown that an observable self-potential anomaly, 10-100 mV in magnitude, can appear on the surface, if the following conditions are satisfied: (1) the circulating fluid is an aqueous solution of neutral $pH (\gtrsim 4)$ and moderate concentration of dissolved salt ($\lesssim 0.1$ mol/l), and (2) the fluid flow rate ranges from 10^{-8} to 10^{-7} m/s. The polarity of the anomaly over a hot zone is always positive whether or not the fluid flow (with nonzero C) intersects the surface; this is mainly because C is negative ($\zeta < 0$) and larger in magnitude under high temperature conditions.

RESULTS OF RECENT SP SURVEYS IN JAPAN

Self-potential (SP) surveys were conducted on five geothermal areas by the Geological Survey of Japan (GSJ) and on two areas by the New Energy Development Organization (NEDO) during the last decade in Japan. Each survey covers an area of 50-100 Km^2 with survey lines of about 100 Km in total length. SP anomalies of various types have been recorded through these surveys, and obvious anomalies of positive polarity are found in five different areas: the Kussharo and Nigorikawa calderas, and the Sengan, Okuaizu and Hohi geothermal areas. In most cases, the correlation between the anomaly of positive polarity and the high temperature upflow zone is evident. Two examples are described here.

Okuaizu geothermal field

The Okuaizu geothermal field is located in Fukushima prefecture on the Japanese island of Honshu. In the area of about 70 km^2, NEDO has completed geological, geochemical, and geophysical explorations including an SP survey, and has drilled 7 1000-1500 m depth wells and 6 ~400 m depth heat holes during 1982-1984. Following NEDO's survey, Okuaizu Geothermal Co., Ltd. (OAG) conducted an exploratory well drilling program in the area.

The area of investigation has a mean elevation of approximately 300-500 m above sea level and is dominated by 729 m Mt. Yuno (Yuno-take). The temperature distribution at -500 m ASL (that is, 500 m below sea level) is shown in figure 3. The high temperature zone is located around wells OA-4 and 6. (The highest temperature observed is 286°C at -1120 m ASL in OA-6.) Well OA-4 was discharged for a month in 1984 and pressure transient tests were carried out (Ishido, 1985).

Also shown in figure 3 is the result of the SP survey; the positive anomaly of about 100 mV overlies the shaded area shown in figure 3. It should be noticed that the northern part of the area of positive anomaly coincides well with that of high temperature and of high productivity wells drilled by OAG (location of OAG's wells is not shown in figure 3).

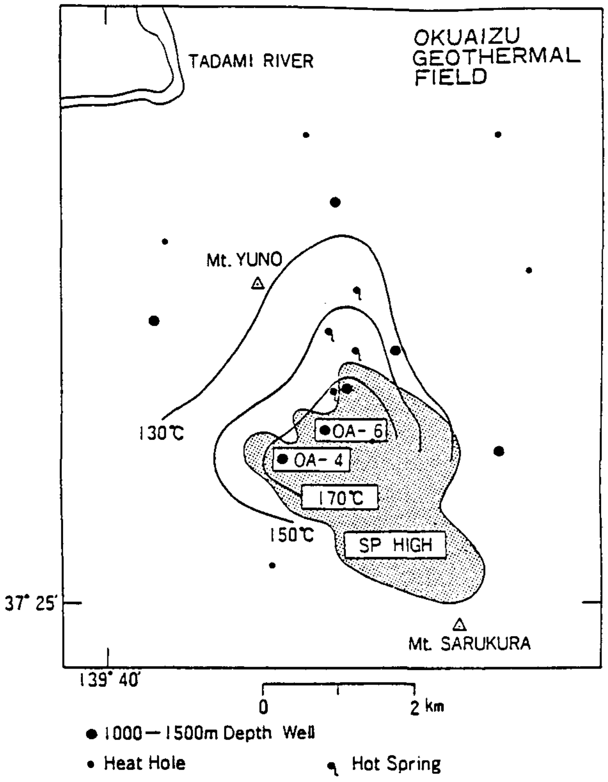

Fig. 3 Geothermal features and location of wells in the Okuaizu field. SP anomaly of positive polarity (~100 mV) overlies the shaded area.

Mt. Yake Volcano area

Mt. Yake (Yake-yama), located in the Sengan geothermal area, northern Honshu, is an active volcano and has many thermal manifestations such as fumaroles, hot springs and alteration zones. Under a joint program, GSJ and/or NEDO have been conducting geological, geochemical, and geophysical surveys and well drilling in the Sengan geothermal area. SP surveys in the Mt. Yake area have been carried out by GSJ since 1979. Exploration efforts were also undertaken by a private developer in the area; Mitsubishi Metal Corporation (MMC) has been running a 10 MW geothermal power plant at Ohnuma since 1974 and conducting an exploratory well drilling program in the Sumikawa field since 1981.

Surface rocks in the area shown in figure 4 are mostly andesitic lavas from Mt. Yake, 1366 m in elevation. The elevations of the fumaroles and hot springs shown in figure 4 are generally from 700 to 1100 m except for the fumaroles near the volcano summit and for the bicarbonate hot springs to the north (520 m). The most remarkable feature of the thermal waters of the area is their compositional variety. Waters discharged from production wells in the Ohnuma field and from exploratory wells in the Sumikawa field have neutral pH

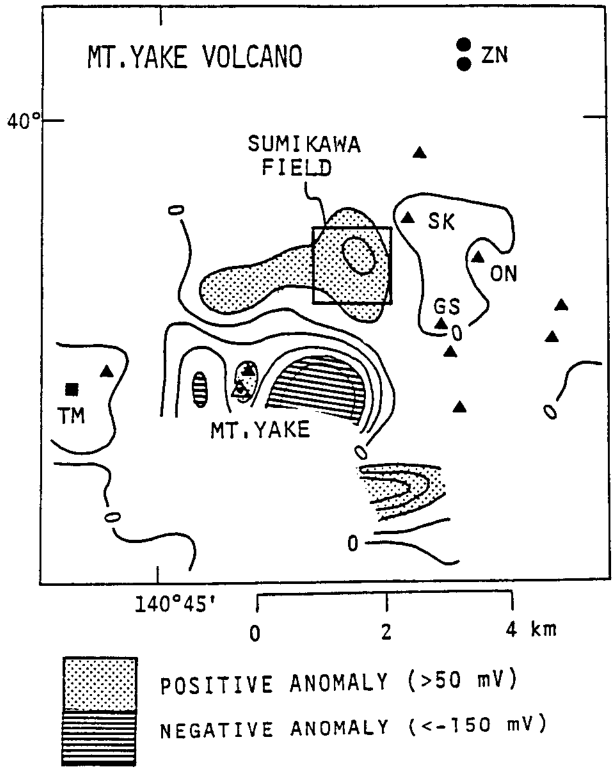

Fig. 4 Self-potential distribution in the Mt. Yake area. Contour interval is 50 mV. Areas with fumaroles and/or steam-heated sulfate type springs are shown as triangles (SK, Sumikawa; ON, Ohnuma; GS, Goshogake). Areas with chloride-bicarbonate type thermal water discharge are shown as solid circles (ZN, Zenikawa). Tamagawa (TM) hot springs area is shown by a solid square.

and total dissolved salt contents of about 2000 ppm on the average (Sakai and Mori, 1981).

The results of the SP surveys are shown in figure 4. Anomalies of positive polarity appear in three areas: at the volcano summit, and on the northern and southeastern flanks of Mt. Yake. The positive anomaly to the north of Mt. Yake overlies the Sumikawa field, where the subsurface temperature is higher than the surroundings (over 250°C at the sea level) and a vapor dominated zone is found at depths of 400-600 m ASL (Kubota, 1985). Considering the chemistry of the subsurface waters in the Sumikawa field, we believe that the subsurface upflow carries enough electric charge (C is large enough) to produce the observed SP anomaly.

Exploration data is not sufficient to characterize the geothermal activity in the area of the positive anomaly southeast of Mt. Yake. We also do not have enough data on the volcano summit area; however, the positive anomaly over 200 mV in amplitude and 500 m in width seems to be associated with the fumaroles there. (To discuss SP anomalies associated with fumaroles, we need more data on the streaming potential generated by the flow of two-phase mixtures of water and steam. Study on this problem is being carried out by Marsden and Tyran (1986).)

As shown in figure 4, there is no obvious anomaly overlying the areas with fumaroles and hot springs except the volcano summit. This is thought to be due to the thermal waters in the areas giving very small C under near surface condition and generating no observable anomaly with their discharge from the surface.

There are two obvious anomalies of negative polarity on the eastern and western flanks of Mt. Yake. The downflow of meteoric waters can generate such negative anomalies through electrokinetic coupling (Ishido, 1981). We do not, however, have enough data for further discussion.

SP CHANGE INDUCED BY PRODUCTION OF GEOTHERMAL FLUIDS

When a sink or source of fluid is created in a reservior as a result of production or injection of geothermal fluids, a surface electric potential anomaly can be produced through electrokinetic coupling if the following coditions are satisfied. The conditions have been derived for electrokinetic effects represented by (1) and (2) without bouyancy terms: there is a boundary separating regions of

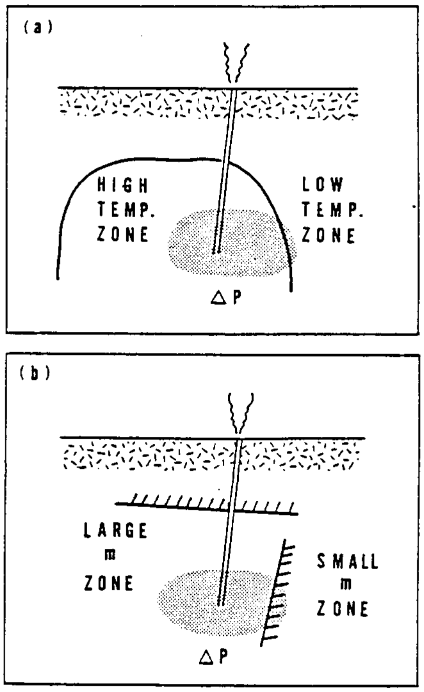

Fig. 5 Models for production-induced SP change. (a) High-low temperature boundary, or (b) large-small hydraulic radius (m) boundary acts as a boundary between regions of differing streaming potential coefficient.

differing streaming potential coefficient C and there is a component of pressure gradient parallel to this boundary (Nourbehecht, 1963; Fitterman, 1978).

A high-low temperature boundary, a boundary between regions of different pore water chemistry, or a contact of different rocks is considered as a candidate for a boundary between regions of differing C in a geothermal reservoir (figure 5). As shown in figure 1, the value of C depends largely on the temperature of the system; therefore, a high-low temperature boundary surrounding a reservoir acts as a boundary between regions of differing C (figure 5(a)). When two kinds of rocks come into contact with each other and other parameters such as pore water chemistry are homogeneous, no major deviations in C are expected for crustal rocks (Ishido and Mizutani, 1981). However, if the value of hydraulic radius (m) of the pores and the cracks varies significantly across the boundary, a large difference in C can appear (Ishido and Mizutani, 1981). A large-small hydraulic radius boundary, therefore, can be a boundary between regions of differing C (figure 5(b)).

When a pressure change induced by production and/or injection of fluids propagates to a boundary between regions of differing C in a reservoir (figure 5), an electric potential anomaly appears on the surface through electrokinetic coupling. We can model the potential generating mechanism quantitatively using the formulation derived by Nourbehecht (1963), Fitterman (1978), and Fitterman (1979). If the boundary is nearly vertical, the anomaly will be dipolar in waveform (Fitterman, 1979).

Production-induced electric potential observed at Nigorikawa

The Nigorikawa caldera is located in the southern part of the Hokkaido island, Japan. The diameter of the caldera is about 3 km and fumaroles and hot springs are distributed in the northern half of the caldera floor. The thermal waters are neutral and contain much HCO_3^-(500-1000 ppm). The concentration of NaCl ranges from 10^{-3} to 10^{-1} mol/l. The Mori geothermal power plant (50 MW) has been built and in operation since 1982. SP surveys were conducted by GSJ three times: in 1978 and 1981 (before plant startup) and in 1984 after the operation of the power plant began.

The result of the 1981 SP survey is shown in figure 6(a); SP is high inside the caldera compared to the surrounding area and anomalies of positive polarity overlie the northern area of hot springs. The results obtained from 1978 survey shows almost the same potential distribution as the 1981 result in the caldera. The SP distribution observed in 1984, however, is significantly different from that in 1981. The difference between the 1981 and 1984 SP distribution is shown in figure 6(b). The dipolar change in SP appears over the main zone of fluid production. The observed change is thought to be generated by the production (and reinjection) of geothermal fluids through electrokinetic coupling. Quantitative modeling of the induced SP change is proceeding on the basis of a formulation similar to that given by Fitterman (1979).

CONCLUSIONS

The correlation between positive SP anomalies and high temperature upflow zones has been confirmed for several geothermal areas in Japan. Quantitative modeling of the electrokinetic effects by Ishido (1981) shows that streaming potential generated by hydrothermal circulation is the most likely cause of the observed positive anomalies. The hydrothermal-circulation-related anomaly may or may not be

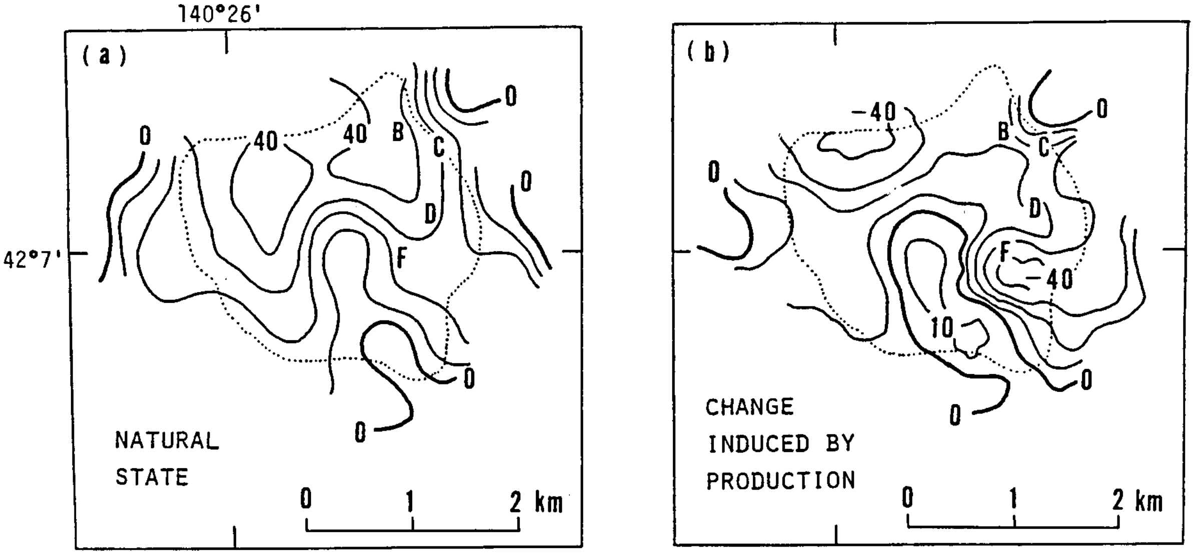

Fig. 6 (a) Self-potential distribution in the Nigorikawa caldera, Japan observed in 1981.
(b) Change in SP induced by production of geothermal fluids. Contour interval is 10 mV.
The edge of the caldera floor is shown by dotted lines. The well sites are shown as B - F.

observable depending upon conditions such as the temperature, the chemical composition of the pore water, the flow rate, and the geometry of the hydrothermal convection cell.

In the neighborhood of an operating geothermal power plant, there is the possibility of the development of production-induced SP change through electrokinetic coupling. The observed change at the Nigorikawa caldera in Japan can be modeled quantitatively using the formulation of Fitterman (1979).

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