MASTER

TOPICAL REPORT

**Self Potential Survey,
Roosevelt Hot Springs, Utah**

by

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UTAH

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Abstract

A large scale (35 km²) self potential (SP) survey was made at Roosevelt Hot Springs. The survey consisted of approximately 47 line-km of profiles at station spacings of 100 m. The profiles were run using a fixed electrode and a traveling electrode out to distances of 1 to 2 km, before advancing the fixed electrode up to the last occupied station. Repeated measurements show a standard deviation of about ± 6 mv, although the spread on groups of measurements might be as large as 30 mv.

Some of the SP profiles show correlations with the thermal system, having generally low values over the thermal high and the coincident resistivity low. Some of the smaller scale features appear to be associated with mapped faults. In plan view, the contoured self potential shows a character very similar to the 300 m, dipole-dipole resistivity. The SP values are generally low, where the resistivity is low. Along the eastern margin of the system, in the vicinity of steep resistivity gradients, the contour map show a series of localized highs.

Electrokinetic (streaming potential) and thermoelectric effects are likely candidates for the sources of these self potential anomalies. The (near surface) hydrothermal clay alteration should increase the cross coupling coefficients for these two effects, although excess clay alteration may reduce the effects through the reduction in electrical resistivity.

Thermoelectric effects, combined with vertical temperature gradients or spherical or point sources below the clay alteration zone (large coupling coefficient), generally produce positive SP anomalies. Negative

thermoelectric anomalies can be produced by point sources within the cross coupling zone (clay alteration), but this would probably be limited to relative shallow sources (less than hundreds of meters). On the other hand, electrokinetic effects combined with various spherical or point sources generally produce negative anomalies. For this reason, the electrokinetic effects might be favored as the source of the large scale low region. Other sources or geometries might be postulated for the localized highs, but their proximity to the steep resistivity gradients might suggest a cause related to the electrical structure.

1.0 Introduction

Self Potential (SP) measurements in geothermal areas have shown anomalous regions associated with the nearsurface thermal zones and faults thought to be fluid conduits. (Zohdy et al., 1973; Corwin, 1975; Anderson and Johnson, 1976; Zablocki, 1976; Combs and Wilt, 1976; Mabey et al., 1978; Corwin and Hoover, 1978). The signs of these anomalies have been both positive and negative.

Possible sources for these self potentials are electrokinetic effects (streaming potentials), thermoelectric effects and chemical potential differences. Streaming potential effects (Appendix A) tend to be slightly favored since the combination of the typical streaming potential coefficient and the force (gradient of the pressure) generally combine to produce effects of larger magnitude from buried spherical or point sources (Corwin and Hoover, 1978). However, strong near surface thermal gradients are capable of producing sizeable selfpotential anomalies (Appendix A).

By definition fluids are moving in a convective hydrothermal system and the system usually has zones of clay alteration. Clay minerals, through their larger cation exchange capacity, aid in the generation of electrokinetic and thermoelectric potentials. However, large percentages of clays and the higher conductivity of hydrothermal fluids would tend to reduce streaming potential effects through the reduction of permeability and the electrical resistivity.

The first SP measurements at Roosevelt Hot Springs were made in 1974 and consisted of a small scale survey utilizing the leapfrog method and a station spacing of 25 m (Ward et al., 1974). Some of the results are

repeated here in figure 1. Several of the lines show a narrow negative anomaly of about 100 mv amplitude. The location of the anomaly is near the top of the Opal Dome where there are fissures showing vertical banding in the opal along the trace of the Opal Dome Fault. These vertical fissures were presumeably the conduits for the thermal waters that built up the opal dome. The width of the anomaly is only slightly more than 100 m indicating that the source is probably quite shallow. Measurements in the vicinity of the old resort hot springs did not show any distinct small scale anomalies.

During the summer of 1978, a preliminary, large scale survey was completed. Approximately 47 km of SP profiles were run; most with a station spacing of 100 m. The survey (figure 2) consisted of 5 east-west profiles and a north-south line to tie all of the profiles to a common datum. Figure 2 also shows the 300 m first separation, dipole-dipole apparent resistivity and the location of the common datum (home pot) point, to which all of the potential measurements are referenced.

2.0 Measurement Procedure

All measurements were made with Cu-Cu $\text{SO}_4(\text{Sat.})$ porous ceramic pots and a high impedance digital voltmeter. The home pot location consisted of a shallow (.5m) hole in which a porous pot electrode was buried, to reduce the effects of temperature fluctuations and changes in soil moisture. Measurements on the nearby surface soil varied between +15mv and +25mv with respect to the buried electrode. At each station location four measurements were taken on a square grid (10 m on a side) and the average of the four readings was taken as the observed potential. Each of the individual measurements was made in a shallow hole approximately 10 cm deep, so that reasonable amounts of soil moisture would be present.

The lines were run using a given fixed electrode and a traveling electrode out to distances of 1 to 2 km, before moving the fixed electrode up to the last occupied station. This procedure helps to reduce some of the errors due to so called pot noise and drift caused by temperature changes, etc. On some occasions, at distances in excess of 1 km, telluric noise could be observed but no attempts were made to correct for this noise other than to average over the higher frequency fluctuations.

Figure 3 shows a detailed survey out to 500 m from the datum electrode at intervals of 25m and 50m. The solid dots are the four individual measurements, the open circles are the means and the horizontal bars show the standard deviations (SD). At the datum station (0W) the two repeated occupations have means a few mv apart and the SD of all eight readings is $\pm 6\text{mv}$. At station 100w there is a higher noise level but the means are within a few mv and the SD is about $\pm 11\text{mv}$. Station 300W illustrates a case

where the means differ by the amount of the SD ($\pm 12\text{mv}$). The overall SD is around $\pm 6\text{mv}$ although groups of measurements can sometimes exhibit a spread of 20mv to 30mv.

In figure 4, from 0 to 1 km E are shown two sets of data taken several weeks apart and on opposite sides of the road. There is general agreement between the two curves in form and magnitude, although in places there are differences as large as 30mv. Also shown in figure 4 are results of another survey (Corwin and Hoover, 1978). The agreement between the two measurements is quite good, note however, that the scale factors differ by a factor of two.

Several of the lines (figure 2) intersect to form closed loops, which provides another check on the accuracy of the measurements. Investigation of the data on these lines show loop errors of around 30mv, in distances of 5km (50 stations).

3.0 Self Potential Data

Figure 5 shows the profile along the road that runs parallel to 2200N and then into Big Cedar Cove. This profile shows what appears to be some rather interesting correlations with the known thermal system. To the east in Big Cedar Cove, in the region of rapidly increasing resistivity the SP profile shows a general high. Over the resistivity low and region of high thermal gradients the SP is low and to the west of the Dome fault the SP returns to higher values. There are several minor features that might even be correlated with specific faults, for example the two minor lows, one associated with the fault crossing the mouth of Big Cedar Cove and the other at the fault west of the Dome Fault. Between these two faults there are minor highs associated with the Dome Fault and F1.

The profile one kilometer to the south (Figure 6) does not show such a distinct character, however. There is no large high to the east, but there is a suggestion of a depressed zone in the thermal area as well as some local positive areas that may be correlated with the Dome Fault and F1.

The profiles on the other lines do not in general show similar correlations. The complex nature of the SP anomaly can be seen in the contour map of figure 7. This map was compiled from all of the data, making some adjustments for the loop errors and with some "eyeball" smoothing. As can be seen from the comparison with the apparent resistivity data (figure 2), there is a lobate region to the west of the southern section that narrows to the north in the vicinity of 3000 to 4000 N. At the northern end there is some widening of the low region as is also seen in the apparent resistivity. On the eastern side things are more

complicated, with a number of highs and lows in the region of the steep resistivity gradients. The lowest resistivity areas ($<10\Omega m$) are generally regions of low SP ($<-50mv$), although there are also low areas outside of the thermal area. As a matter of fact the most negative region is in the southeast corner, up against the flank of the Mineral Range.

There are also a number of isolated positive regions, notably a pair in the mouth of Big Cedar Cove and another central one between 3000 and 4000N, just to the east of the baseline. There is also the suggestion of a positive trend extending from the ridge in the southeast, to the central high (noted above) and off as a weak ridge to the northeast. Most of the producing wells are along this trend (figure 2) and well 25-15 is just to the southwest of the high in Big Cedar Cove.

4.0 Conclusions

As with other geothermal areas, Roosevelt Hot Springs has SP anomalies associated with the near surface thermal zone. The nature of the SP pattern is complex, consisting of low areas correlating quite well with the low resistivity regions but also containing positive areas in the vicinity of some of the producing wells. The source(s) of these SP anomalies is not known, although many have been suggested in the past. A likely candidate is the electrokinetic streaming potential because its magnitude is relatively larger for typical geological materials. It doesn't seem likely that the source(s) will be determined until much more is known about the nature of the cross coupling coefficients in materials from geothermal areas and the nature of the flows (fluids, heat etc.) in some well understood geothermal area.

Consideration of the models in Appendix A, show the expected thermoelectric anomaly, due to the large nearsurface thermal gradient, would be positive over the thermal region. The observed anomaly is generally negative over this region although there are some positive areas. On the other hand, the streaming potential anomalies for the preferred models in Appendix A would be negative over the regions ascending fluids, which would tend to favor electrokinetic effects as the source mechanism.

Also in considering what one might call an anomaly one needs to know the nature of the background SP in a "normal" area. This survey was by and large confined to the anomalous zone, however some limited measurements off the southern end seem to indicate that the Mineral Range is negative with respect to the valley with steep gradients along the range front. This is

in agreement with some measurements in other areas showing increasing negative SP with increasing altitude (Corwin and Hoover, 1978). More measurements to the north and south of the system are needed to put the thermal anomaly region in context.

APPENDIX A

Electrokinetic Coupling

The streaming potential effects due to the coupled flow of electrolyte and electrical current are not always intuitively obvious and therefore it is helpful to consider some simple cases. The basic equations to consider are the solvent flow equation (A-1) and the coupled electric current flow equations (A-2).

$$\Gamma = -k\nabla P \quad (\text{flux of electrolyte}) \quad \text{A-1}$$

$$J = -\Gamma\nabla\phi - L_{pq}\nabla P \quad (\text{flux of charge}) \quad \text{A-2}$$

where

k = permeability

σ = conductivity

L_{pq} = streaming current coefficient

P = pressure

ϕ = electric potential

L_{pq}/σ = streaming potential coefficient = α

Equation A-2 can be rewritten in terms of the generalized or pseudopotential ψ as

$$J = -\sigma\nabla\psi \quad \text{A-3}$$

where

$$\psi = \phi + \alpha P \quad \text{A-4}$$

For no external current sources

$$\nabla \cdot J = 0$$

and therefore

$$\nabla^2\psi = 0 \quad \text{A-5}$$

the boundary conditions are then

$$\psi^1(b) - \psi^2(b) = (\alpha_1 - \alpha_2)P(b) \quad A-6$$

from the continuity of P and ψ on the boundary (b) , and

$$\sigma_1 \frac{\partial \psi_1}{\partial n} = \sigma_2 \frac{\partial \psi_2}{\partial n} \quad A-7$$

from the continuity of the normal current (n) across the boundary. The current flow has two components (A-3 and A-4) one driven by an electric potential and another due to the pressure through the streaming current coefficient.

A simple case to consider is the point source of pressure in a medium with only a contrast in the streaming potential coefficient (figure 1a).

The potentials are (from A-3 through A-7):

$$\psi_1 = (\alpha_1 - \alpha_2) \frac{P_o a}{2} \frac{1}{[r^2 + (Z_o - Z)^2]^{\frac{1}{2}}} \quad A-8$$

$$\phi_1 = \psi_1 - \alpha_1 P_o a \frac{1}{[r^2 + (Z_o + Z)^2]^{\frac{1}{2}}} \quad A-9$$

$$\psi_2 = (\alpha_1 - \alpha_2) \frac{P_o a}{2} \frac{1}{[r^2 + (Z_o + Z)^2]^{\frac{1}{2}}} \quad A-10$$

$$\phi_2 = \psi_2 - \alpha_2 P_o a \frac{1}{[r^2 + (Z_o + Z)^2]^{\frac{1}{2}}} \quad A-11$$

The total current flow pattern for a positive pressure source and $\alpha_1 > \alpha_2$ is shown in figure 1b. Note that even though the pressure driven streaming current is radial outwards, from medium 1 into 2, that the total current circulates from medium 2 into medium 1. Consideration of the electrically driven currents ($-\sigma \nabla \phi$) shows that they are set up so as to drive return currents to the regions of charge deficiency at the pressure source and/or the interface (depending on the magnitudes of α_1 and α_2). The direction of the current flow will be reversed for $\alpha_1 < \alpha_2$, however note that the sign of the (real) electric potential (A-11) remains negative. In this case then we see that the potential ϕ_2 (the real electric potential that would be measured in medium 2) remains the same no matter what the relative magnitudes of α_1 and α_2 , and in spite of the reversal in the direction of the total current.

The above example is geometrically quite simple but it does illustrate some subtle and perhaps unexpected effects. A more realistic model would include the air-earth interface. Nourbehecht (1963) considered such a model. The boundary condition he used was that the pressure was zero on the interface and this was accomplished by using an image pressure source of opposite sign in the air (figure 2a). However, this distribution of pressure sources gives a nonzero pressure gradient at the surface and implies a flow (a spring) across the interface. If a like pair of pressure sources (figure 2b) are utilized, there is no flow across the interface and the surface is not an equipotential. This would correspond to the air-earth interface being an impermeable boundary. This might correspond more closely to the actual flow in a homogeneous earth, where a perturbation in the water table would lead to a more or less horizontal

flow just below the water table and away from the pressure source (figure 2C).

Considering the model in figure 2d, with only a contrast in streaming potential coefficients, Nourbehechts' pressure model with a negative sign for the image pressure ($P(z=0)=0$) gives for the electrical potential on the surface.

$$\phi_1(r, Z=0) = (\alpha_1 - \alpha_2) P_0 a \left(\frac{1}{[r^2 + Z_0^2]^{\frac{1}{2}}} - \frac{1}{[r^2 + (Z_0+2d)^2]^{\frac{1}{2}}} \right) \quad A-12$$

This potential can be positive or negative depending on the magnitudes of α_1 and α_2 . If the image source has the same sign ($dP/dz|_{z=0} = 0$) the potential on the surface is

$$\phi_1(r, Z=0)^* = -(\alpha_1 + \alpha_2) P_0 a \frac{1}{[r^2 + Z_0^2]^{\frac{1}{2}}} + \alpha_1 P_0 a \frac{1}{[r^2 + (Z_0+2d)^2]^{\frac{1}{2}}} \quad A-13$$

this potential is always negative ($P_0 > 0$) no matter what the relative magnitudes of α_1 and α_2 . These two models give quite different results. The latter model (A-13), which probably represents the real flow more accurately, always produces a negative anomaly over a positive pressure source. It should also be noted that A-13 gives an anomaly even for a

homogeneous earth ($\alpha_1 = \alpha_2$), while Nourbehecht's model (A-12) does not.

Bogoslovsky and Ogilvy (1973) reported a positive self potential anomaly over a shallow pumping well (negative pressure source) which would agree with equation A-13. For the measured pressure gradient this would require a streaming potential coefficient of about 30 mv/atm, which is not an unreasonable number.

Thermoelectric Coupling

The coupled equations for this case are

$$\Gamma_h = -K\nabla T \quad (\text{heat Flux})$$

$$J = -\sigma\nabla\phi - L_hq\nabla T \quad (\text{charge Flux})$$

where

K = thermal conductivity

L_{hq} = cross coupling coefficient between temperature and charge

T = temperature

ϕ = electric potential

These equations can be solved for the coupled flows as was done for the electrokinetic coupling with the substitution of T for P , K for k and thermoelectric potential coefficient ($c = L_hq/\sigma$) for α .

the boundary condition at the air-earth interface in the case of heat flow is more appropriately one where the surface is an equipotential and a flux of heat is allowed across the interface. The point source electrokinetic models, using Nourbehecht's (1963) boundary condition are then appropriate for studying the thermoelectric effects. The results of those models can then be used by making the substitution noted above.

Another case of interest in thermoelectric studies is the anomaly caused by a change in properties in the presence of a strong vertical temperature gradient. Nourbehecht (1963) gave several samples of the effects due to vertical contacts and dikes in the presence of vertical chemical potential gradients and the results are easily adapted to the thermal problem.

Figure 3a shows the geometry of a vertical contact in the presence of a vertical temperature gradient expressed as

$$T(Z) = T_0 (1 - e^{-kZ}) \quad A-16$$

Taking $T_0 = 250^\circ\text{C}$ and $k^{-1} = 500\text{m}$ we would have a nearsurface gradient of 500°C/km and a temperature at depths greater than 1km of about 250°C . These values are in reasonable agreement with data from Roosevelt Hot Springs.

Using the thermal model of A-16 we can solve for the electrical potential on the surface

$$\phi_1(x, Z=0) = -\phi_2 = (c_1 - c_2) T_0 (.5 - B(x)) \quad A-17$$

where

$$B(x) = \frac{1}{\pi} (C_1(kx) \sin kx - S_2(kx) \cos kx) \quad A-18$$

$$C_1(kx) = - \int_{kx}^{\infty} \frac{\cos t}{t} dt, \quad S_1(kx) = - \int_{kx}^{\infty} \frac{\sin t}{t} dt \quad A-19$$

The normalized potential $(\phi/(c_1-c_2)T_0)$ is plotted in figure 3b. For our thermal model $kx=1$ at $x=500\text{m}$ so the anomaly would extend for several km

horizontally. Thermoelectric coefficients are often of the order of several tenths of a mv/°C, so that anomalies of the order of 50 mv could be possible. The anomaly would be positive over the region with the stronger thermoelectric coefficient. Since the hydrothermal system is often covered by a near surface zone of clay alteration and since clays generally tend to increase the cross coupling coefficients one might expect to get positive anomalies.

Of course this is an extremely simple model, a better one might use a dike-like body rather than a vertical contact. The results of Nourbehecht's (1963) calculations show that for a vertical dike with $kt=1$ (t =thickness=500m) the maximum value of the anomaly would be reduced by about 50% compared to the single vertical contact.

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 1a

Figure 1b

Figure 2a

Figure 2b

Figure 2c

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Figure 3a

Figure 3b

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