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Reply to comment by Revil on "Rapid Fluid Disruption: A source for self-potential anomalies" by M. J. S. Johnston, J. D. Byerlee, and D. Lockner

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INDEX TERMS: 8494 Volcanology: Instruments and techniques; 8424 Volcanology: Hydrothermal systems (8135); 0925 Exploration Geophysics: Magnetic and electrical methods; 0619 Electromagnetics: Electromagnetic theory; 0694 Electromagnetics: Instrumentation and techniques; *KEYWORDS:* self-potential volcanoes, fluid flow, electrokinetic, conductivity, charge

[1] Large positive self-potential (SP) anomalies are observed around active volcanoes [*Zablocki*, 1976; *Zlotnicki and Le Mouel*, 1990; *Michel and Zlotnicki*, 1998; *Hashimoto and Tanaka*, 1995], above burning coal mines [*Corwin and Hoover*, 1979], and around vents in geothermal areas [*Zohdy et al.*, 1973; *Corwin*, 1976]. Various physical mechanisms have been proposed as contributors to these potentials below and above the boiling point of crustal liquids. These include electrokinetic (EK) potentials [*Nourbehecht*, 1963], diffusion potentials as commonly observed in well logs at material boundaries [*Morgan et al.*, 1989] and thermoelectric potentials [*Nourbehecht*, 1963; *Dorfman et al.*, 1977].

[2] Our original paper [*Johnston et al.*, 2001] has two main points. First, that laboratory experiments demonstrate a "new" process which we refer to as rapid fluid disruption, or RFD, for separating electric charges in porous media. Second, that this RFD effect may lead to significant electric field potentials near active volcanoes due to the interaction of hot rock and ground water.

[3] To demonstrate these points, we showed field and laboratory results indicating large positive potentials are generated when pore water is vaporized. We considered situations where there was little or no free water so that these effects would not be confused with potentials generated by electrokinetic (EK) effects. In particular, we showed large SP anomalies over vents on Kilauea, Hawaii, where the water table is more than 500 m deep and suggestions of convecting flow needed to drive EK potentials are not realistic (Figure 1 of *Johnston et al.* [2001]). We showed laboratory experiments where small amounts of water are introduced into a simulated vent filled with crushed granite in a hot dry granite rock sample. When a few tens of cubic centimeters of water were introduced and vaporized within the sample (Figure 3 of *Johnston et al.* [2001]), large positive potentials exceeding 5 V were observed if measured with a Keithly electrometer or greater than 50 mV if measured with a digital recorder having a 10 Mohm input impedance.

[4] If more water is introduced (Figure 4 of *Johnston et al.* [2001]) and the temperature near the input is driven below 100°C, the initial positive potential is followed by a prolonged negative voltage anomaly. However, if this same amount of water is introduced slowly the potential remains positive as the introduced water boils off. We suggest that the initial positive potentials result from rapid fluid disruption and that this process may be an important contributor to positive potentials seen around active volcanic vents. We further show that the charge generation observed is 10^{-4} C/kg of water similar to that observed by *Blanchard* [1964] for water vaporization. The secondary negative potentials observed with larger amounts of water which drove the near-input temperature below 100°C, and which persisted in some cases for more than a minute, we attributed to electrokinetic effects. At room temperature, we also show that forcible removal of water from the crushed granite in the simulated vent with compressed air, thus forming a mist above the sample, also generates a positive transient in potential. We suggested both RFD and EK processes contribute to this result.

[5] In the comment, *Revil* [2002] proposes that all these effects, including the laboratory data, can be explained by electrokinetic effects. We summarize Revil's main arguments as follows: (1) The EK effects explain the initial positive potential for our hot rock sample even though no liquid actually flowed through the sample. (2) The amplitudes of the initial positive pulse we observed are what would be expected for this sample since they are comparable with extreme range EK measurements of andesitic ash by *Jouniaux et al.* [2000]. (3) Field evidence exists to support the underground fluid flow patterns he proposes for active volcanoes. (4) RFD effects in Figure 4b of *Johnston et al.* [2001] should again occur at $t > 13.2$ min even though there was no liquid (or steam) in the sample. (5) The secondary negative potentials observed in Figure 4a of *Johnston et al.* [2001], when larger fluid injection volumes dropped the input temperature below 100°C, result from a reverse EK potential. (6) Potentials generated by gas removal of moisture in the gouge of a dry rock result only from EK effects. (7) Finally, he disagrees that rocks will become extremely resistive when all liquids are boiled off.

[6] Before responding to Revil's comments, we wish first to point out that the experiments that we report are very different from those referenced by Revil describing EK effects. In our experiments we have no direct flow of pore

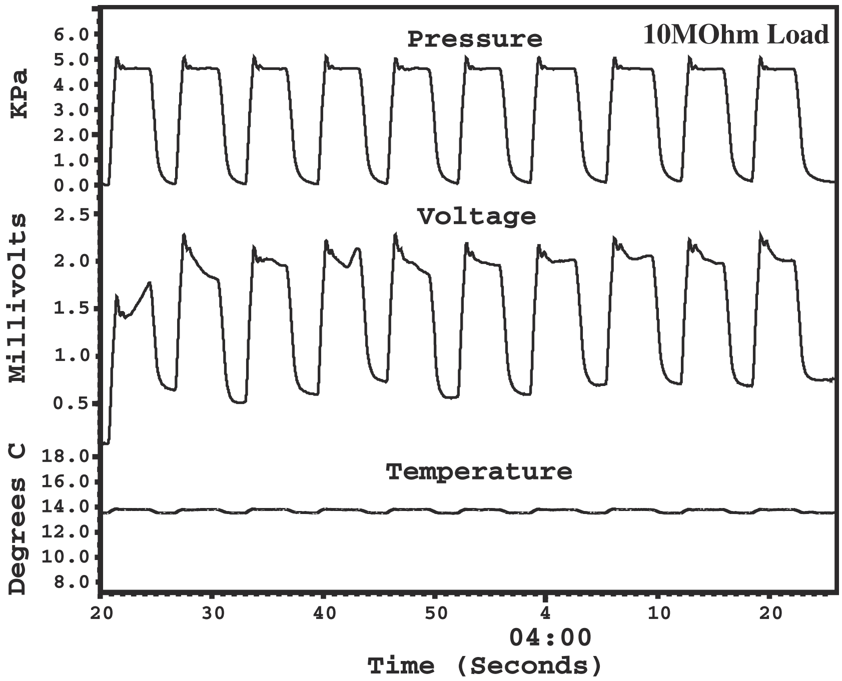

Figure 1. Simultaneous pressure, voltage, and temperature for repeated injection of water at 0.005 MPa in the sample setup described by *Johnston et al.* [2001].

water. We are essentially vaporizing water within gouge material in hot rocks. Only when sufficient cold water is introduced such that the local temperature falls below the boiling point that local EK effects may occur and these are second order effects. We also do not have saturated samples. The majority of the sample remains at a temperature far above the boiling point of water. Charge decay tests on the heated sample prior to water injection indicate a resistivity in excess of 10^7 ohm m. Nevertheless, to place Revil's comments in context, we have conducted an experiment similar to his in which we repeatedly start and stop continuous water flow through the sample at room temperature (see Figure 1). Note that in this case the rock was wet and its resistivity was much lower than that for the hot dry rock experiments. Thus the observed voltage changes did not depend on the impedance of the measuring system.

[7] Figure 1 shows 10 cycles of pressure, voltage and temperature obtained for pressure changes of 0.005 MPa using the same apparatus described by *Johnston et al.* [2001]. The water is Menlo Park tap water that originates as snow melt on the Sierra Nevada granite. The measured pH was 6.8. Each cycle at different pressures was repeated 20 to 30 times. The pressure data were corrected for the small static head of water in the apparatus, and the voltage data were corrected for electrode offset. The small temperature variation from 13.65°C to 13.95°C results from the small temperature difference between the sample and the water reservoir. The average coupling coefficient obtained was 288 mV/MPa. This is similar to the values obtained for Westerly granite by *Morgan et al.* [1989]. Slightly lower values of 268 mV/MPa were obtained at a higher 0.037 MPa pressure variation. As observed by *Morgan et al.* [1989] and *Jouniaux and Pozzi* [1997], higher values would of course be obtained if high concentrations of Na^+, K^+, Al^{3+}, or Ca^{2+} ions were added to the water. However, this is not the point for the experiments that we report. The issue here concerns whether the electric potentials we observe could be explained by EK effects. Based on these room temperature observations the maximum EK effect that could be produced at our peak pressure of 0.1 MPa is about 27 mV provided continuous flow was maintained through the sample. We do not have continuous flow. We have no flow into or out of the sample or in the surrounding rock. So, if EK effects do occur, they are occurring within the gouge and the sense of flow is opposite to the flow of steam. Hence the generated potential would be smaller than we observe for RFD effects if we have the same pressure gradient and the sign would be opposite. We discuss below a demonstration of this.

[8] Thus the issues here are more complex than proposed by Revil. The sign of EK effects are indeed positive in the direction of flow but the flow in the cases we consider (where there is enough liquid to have flow) is opposite to that expected by Revil and thus the sign is opposite. In retrospect, we should have included this EK experiment in our original paper. This could have allowed quantitative comparison of the two effects and would have probably helped readers better understand our experimental results. With this as background we can now respond to Revil's points.

1. Can the Sign of the Initial Positive Potentials Be Explained by an EK Effect?

[9] The sign of the initial positive potentials could be explained by EK effects if we had liquid flowing through the sample as shown in Figure 1 and as suggested by *Revil* [2002]. However, we cannot see how the initial positive potentials can be explained this way since there is no liquid flow through the sample. In no case did we inject enough water to fully saturate the gouge although injection of

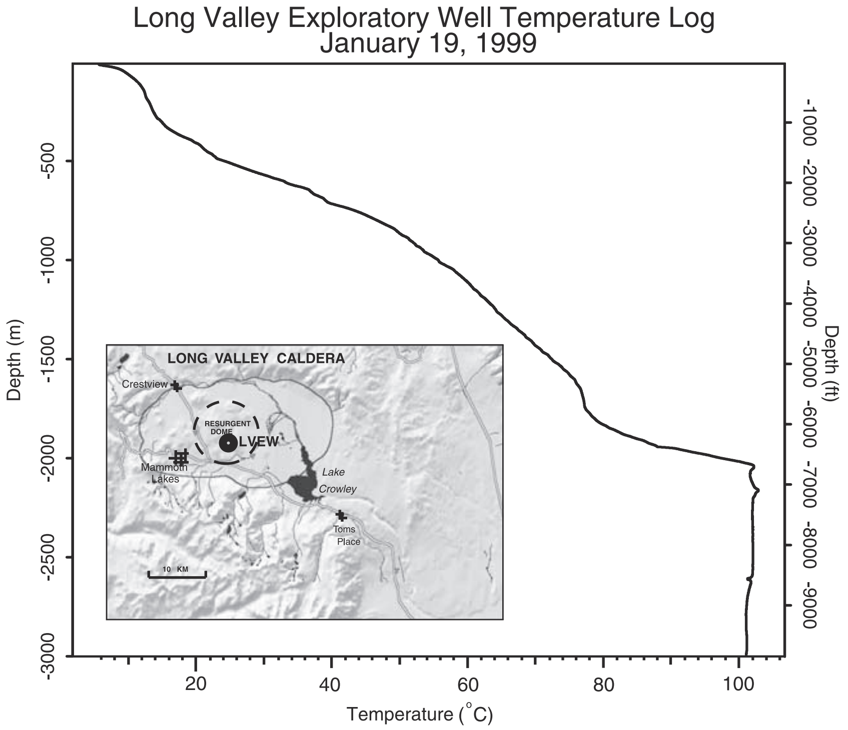

Figure 2. Temperature as a function of depth 3 months after the final drilling in the Long Valley deep well, LVEW (courtesy of R. Jacobson, personal communication, 2001). LVEW is the only 3-km-deep well on an active volcano worldwide that might provide direct verification of deep fluid flow. These data are not consistent with simple large-scale convective flow such as proposed by *Revil* [2002].

30 cm^3 of water does come close if the rock is cold. The primary effect we see is from water vaporization.

2. Can the Amplitude of the Initial Positive Potentials Be Explained by an EK Effect?

[10] Even if liquid flow was continuous through our sample, the maximum EK effect we would expect to see is less than 27 mV for a 0.1 MPa pressure gradient. This is small compared with the 5 V we see using a Keithly electrometer to record the potential. Thus the answer is a clear no.

3. Does Field Evidence Exist for Proposed EK Liquid Flow Systems on Volcanoes?

[11] Revil objects to our statement "many of the recent models... postulate complex groundwater circulation systems for which there are no supporting field observations." To support speculation about underground liquid flow in a volcano, we need some way to verify the geometry of this flow. We know of no such data showing underground liquid flow geometry. Some hints might be obtained from deep boreholes drilled around the vents and on the slopes of the volcano. However, this is an expensive and exceedingly difficult task. Of the few deep boreholes that have been drilled on volcanoes (e.g., Unzen, Long Valley, Kilauea), the data do not support suggestions of the simple large-scale liquid flow proposed by the *Ishido and Prichett* [1999] and *Revil et al.* [1999] models. As an example, we can consider the deepest of these boreholes (3 km) on the resurgent dome in Long Valley, California, beneath which recent intrusions have occurred from 1989 to 1998 [*Langbein et al.*, 1995]. A positive SP anomaly has long been observed over the resurgent dome [*Anderson and Johnson*, 1976] and recently confirmed [*Zlotnicki et al.*, 1999]. The temperature data (shown in Figure 2, courtesy of R. Jacobson, personal communication, 2001) indicate a varying depth gradient above 2 km with temperature almost constant but slightly decreasing from about 102°C at 2 km to about 101°C at 3 km. These data imply a complex three-dimensional (primarily) horizontal and (some) vertical flow (both down and up around the hole) [*Sorey et al.*, 1991; D. Pribnow et al., Fluid flow in the resurgent dome of Long Valley caldera: Implications from thermal data and deep electrical sounding, submitted to *Journal of Geophysical Research*, 2002] rather than a simple upward flow as proposed by *Revil et al.* [1999]. Clearly, this issue is extremely complex, and we stand by our statement that there are no existing field observations supporting the liquid circulation systems suggested to explain SP measurements on volcanoes. Note that we are not saying the models are wrong, only that there are no independent flow data to support them.

4. Should RFD Effects be Expected in Figure 4b of *Johnston et al.* [2001] at $t > 13.2$ min?

[12] At time $t > 13.2$ min in Figure 4b of *Johnston et al.* [2001] the last of the water has been boiled out of the gouge. As water was initially slowly introduced the temperature near the input remained, except for the initial 1.5 s, above 100°C. The temperature farther into the gouge

remained above 100°C, and a positive potential was maintained as the water was boiled off. Injection ceased at about 10:11 min, about 45 s after starting. Injection can be seen as increased voltage noise during this time since it was hard to maintain uniform slow injection. After $t > 13.2$ min, there was no longer any water in the sample, and therefore there cannot be any RFD effects even though the temperature has risen above the boiling point.

5. Can the Secondary Negative Potentials in Figure 4a of *Johnston et al.* [2001] Result From a Reverse EK Effect?

[13] Once injection was completed, the valve was closed and any subsequent flow of water was confined to the pore space within the gouge. Could the negative potentials result from EK effects? In our paper we do attribute these negative potentials to EK effects in which case net pore water flow is downward and in the opposite direction of steam flow. Thus the sign is consistent with that proposed by *Revil* [2002]. We extended the experiment shown in Figure 4a of *Johnston et al.* [2001] by first heating the sample to 250°C, then injecting water until the gouge was saturated (i.e., we could see water at the top of the sample). In this case we have the situation where the gouge in the middle of the cylindrical sample is at, or below, 100°C and the outside rock is at 250°C. Steam bubbles are seen coming though the water, but no water is flowing into or from the sample. We expect that water is flowing turbulently within the gouge in a direction opposite to the steam bubbles (to replace the vaporized water), and it is this flow that we suggest results in EK effects. For this situation we generate a negative potential of −140 mV which slowly approaches zero as all the water is boiled from the sample and the temperature in the gouge rises above 100°C, as shown in Figure 4a of *Johnston et al.* [2001]. We believe that this experiment clarifies the problem of sign that has confused Revil. While this issue is of secondary importance to the main focus of our paper, it is nevertheless an important problem in most field situations where separation of these sources is not easy.

[14] We also checked whether thermoelectric effects [*Nourbehecht*, 1963] may contribute to the observed negative potentials. To investigate this issue, we allowed the rock (without water present) to be heated to 250°C and then cooled the lower section by 50°C by attaching a heat sink to see whether we could generate negative potentials. The thermoelectric effect observed was +0.45 mV and thus appears to be a minor contributor to these processes and cannot explain these negative potentials.

6. What Fraction of the Signal Generated by Gas Removal of Water in Rock Gouge Within a Dry Rock Results From EK? (See Figure 5 of *Johnston et al.* [2001])

[15] While we state in our paper that both RFD and EK effects may be contributing to the observed potentials, we are not able in the short time that we have to respond to Revil's comments to conduct experiments that show separation between the two processes. Probably, part of the initial signal (before a gas path has been established through the sample in the first seconds) results from EK and part of the later signal (when there is no free liquid) results from RFD.

7. On the Generation of More Resistive Regions Above Hot Sources When Pore Fluids Are Boiled Off

[16] We are well aware that wet volcanic rocks are conducting. The issue here concerns what happens when the liquids are boiled off in a region immediately above a hot source. In our particular granite sample the conductivity changed from about 10^{-3} S/m when the sample was water saturated to less than 10^{-7} S/m when it was heated. Similar results were obtained for wet and dry basalt samples. Other similar data have been reported in *Clark* [1966]. Thus resistive inclusions should be expected when all liquids are removed from hot rocks. However, these inclusions should not be expected to occur on a large scale, and as we say in our paper, it will be difficult to demonstrate their existence using inversion of magnetotelluric (MT) or direct resistivity data on volcanoes where the surrounding rocks are extremely conducting with conductivities of near-surface materials sometimes exceeding 0.1 S/m. Nevertheless, we report suggestions of such a resistivity increase during the eruption of Izu-Oshima [*Yukutake et al.*, 1990] and see no reason to change this implication regarding possible indications of vent activity.

8. Conclusions

[17] In summary, we do not believe that EK effects can explain our hot rock data, as suggested by *Revil* [2002]. While his lengthy discussion of the origins of EK potentials is accurate and well presented, it is incorrectly applied to the test conditions occurring in our experiments. Revil's explanation follows from two (incorrect) assumptions about our experiments:

1. We had water flowing through our sample for the hot rock experiments. (We do not, only steam came out of the rock).
2. We have an EK effect for our experiment that is orders of magnitude larger than actually observed if it is further assumed that water does flow through the sample.

[18] We reaffirm our position that RFD effects may contribute significantly to the SP anomalies observed around active volcanoes.

[19] **Acknowledgments.** We thank Ron Jacobson for providing the temperature data shown in Figure 2 and Doug Myren for help with recording.

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