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# Rapid fluid disruption: A source for self-potential anomalies on volcanoes

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**Abstract.** Self-potential (SP) anomalies observed above suspected magma reservoirs, dikes, etc., on various volcanoes (Kilauea, Hawaii; Mount Unzen, Japan; Piton de la Fournaise, Reunion Island, Miyake Jima, Japan) result from transient surface electric fields of tens of millivolts per kilometer and generally have a positive polarity. These SP anomalies are usually attributed to electrokinetic effects where properties controlling this process are poorly constrained. We propose an alternate explanation that contributions to electric fields of correct polarity should be expected from charge generation by fluid vaporization/disruption. As liquids are vaporized or removed as droplets by gas transport away from hot dike intrusions, both charge generation and local increase in electrical resistivity by removal of fluids should occur. We report laboratory observations of electric fields in hot rock samples generated by pulses of fluid (water) through the rock at atmospheric pressure. These indicate the relative amplitudes of rapid fluid disruption (RFD) potentials and electrokinetic potentials to be dramatically different and the signals are opposite in sign. Above vaporization temperatures, RFD effects of positive sign in the direction of gas flow dominate, whereas below these temperatures, effects of negative sign dominate. This suggests that the primary contribution to observed self-potential anomalies arises from gas-related charge transport processes at temperatures high enough to produce vigorous boiling and vapor transport. At lower temperatures, the primary contribution is from electrokinetic effects modulated perhaps by changing electrical resistivity and RFD effects from high-pressure but low-temperature $CO_2$ and $SO_2$ gas flow ripping water molecules from saturated crustal rocks. If charge generation is continuous, as could well occur above a newly emplaced dike, positive static potentials will be set up that could be sustained for many years, and the simplest method for identifying these hot, active regions would be to identify the SP anomalies they generate.

## 1. Introduction

Observations of self-potential (SP) anomalies near dikes, vents, recent intrusions, geysers, and hot springs on volcanoes and in geothermal areas have long been used as an easy method for identification and delineation of these regions [*Corwin and Hoover*, 1979]. The SP anomalies have primarily been attributed to electrokinetic (EK) effects [*Nourbehecht*, 1963], generated from the hydrothermal circulation system within the volcano and, most particularly, from heat-generated fluid flow near regions of dike injection. However, many of the recent models [*Ishido and Pritchett*, 1999; *Revil et al.*, 1999; *Adler et al.*, 1999] postulate complex groundwater circulation systems that are sometimes opposite in sense and, for which, there are no supporting field observations. Small negative anomalies are also expected from thermoelectric effects [*Corwin and Hoover*, 1979], with other minor contributions of various signs expected from electrochemical effects, electrode noise, resistivity variations, and telluric noise.

In this paper we suggest rapid fluid disruption (RFD) as an additional, and perhaps more important, source of crustal charge generation that leads to self-potential anomalies. Our laboratory measurements indicate RFD effects are much more effective at producing large concentrations of charge in the Earth's crust above these active regions. More important, the expected removal of fluids from the rocks near these regions resulting from vaporization of liquids and transport of hot gases away from hot dike intrusions would dramatically change the electrical resistivity structure, changing localized resistivity in regions from moderate resistivity (10-100 ohm m) to high resistivity ($> 10^5$ ohm m) although detection of a high-resistivity region within a conducting matrix may be difficult. However, the continued generation of substantial charge and slow decay in these noncon-



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ducting environments would lead us to expect long-term self-potential anomalies, similar to those observed. In contrast, thermal anomalies associated with this process may not be apparent for many tens of years because of the poor thermal conductivity of crustal rocks [*Stacey*, 1992].

The study of self-potential anomalies generated by volcanoes was pioneered by *Zablocki* [1976] and others on Kilauea volcano in the 1970's (see top of Figure 1, from *Heliker et al.* [1986] for the *Jackson and Kauahikaua* [1987] profile over the east rift zone). Other observations were made in geothermal regions [*Zohdy et al.*, 1973; *Corwin*, 1976], over burning coal mines [*Corwin and Hoover*, 1979], and in the Long Valley volcanic caldera to investigate caldera structure [*Anderson and Johnson*, 1976], but further systematic efforts to observe these phenomena were not made until recent work on Piton de la Fournaise volcano on Reunion Island in the Indian Ocean [*Zlotnicki and Le Mouel*, 1990; *Michel and Zlotnicki*, 1998] and in Japan on Unzen volcano [*Hashimoto and Tanaka*, 1995]. In both of these later experiments, clear anomalies in potential were observed around the vents and domes formed as a consequence of major eruptions (see for example, the bottom of Figure 1 from *Hashimoto and Tanaka*, [1995]), and most importantly, transient variations of up to 1200 mV occurred in association with fissure eruptions. These transients decayed over the next month.

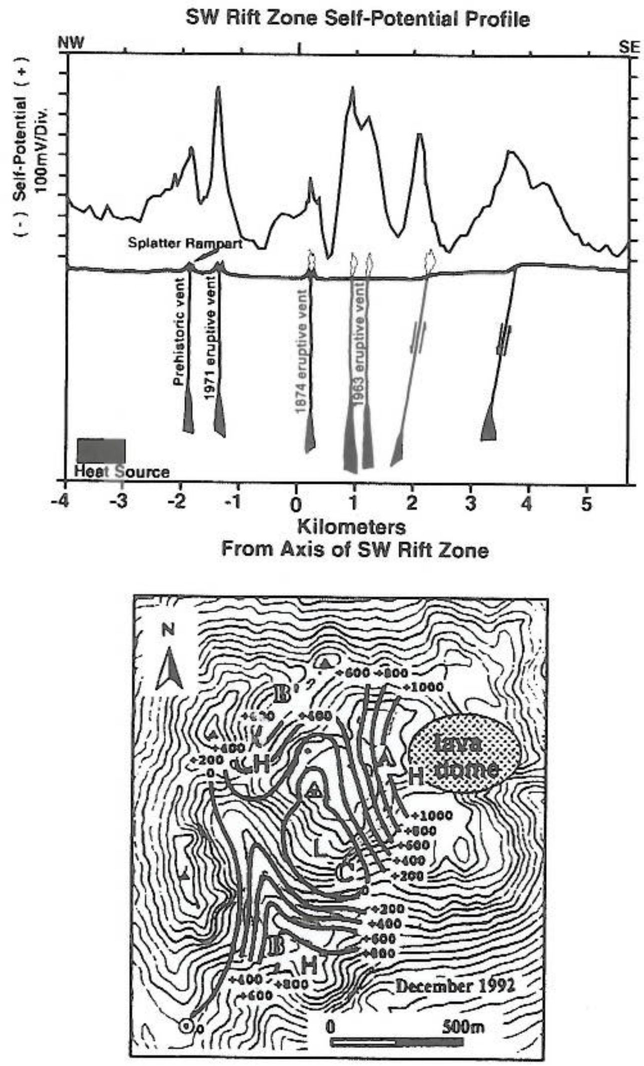


**Figure 1.** (top). Self-potential profile across numerous vents in the southwest rift zone of Kilauea (from *Heliker et al.*, [1986]). (bottom). Contours of self-potential (in millivolts) on Unzen volcano in December 1992 [from *Hashimoto and Tanaka*, 1995]). The lava dome marks the eruption site.

In this paper, we will restrict our focus to the self-potential anomalies generated in the relatively quasi-static state around active vents in geothermal regions and on volcanoes. In this circumstance the primary physical processes are just RFD and EK effects. We use laboratory measurements of a simulated vent to identify the relative importance of RFD and EK effects above and below the boiling point of water. We suggest that RFD processes could be responsible for many recent observations of large positive anomalies around vents on volcanoes. This work has implications for the future detection of active dikes and sills and, more importantly, for detection of changes in intrusion activity.

Other mechanisms can of course generate substantial charge on, and particularly above, volcanoes during violent eruptions and can have many consequences, including spectacular lightning. These shock mechanisms include piezoelectric effects [*Finkelstein et al.*, 1973; *Baird and Kennan*, 1985], rock shearing/triboelectricity [*Lowell and Rose-Innes*, 1980; *Gokhberg et al.*, 1982; *Brady*, 1992], fracto-emission [*Donaldson et al.*, 1988], and magma fragmentation into ash [*James et al.*, 1998]. Each of these mechanisms has a sound physical basis with support by laboratory experiments, and each is capable of producing substantial charge on and in the atmosphere above volcanoes during eruptions. During steady state conditions such as those considered here, these processes do not contribute or maintain charge for any appreciable length of time in the conducting crust surrounding volcanoes [*Johnston*, 1997].

## 2. Physical Background

Electrokinetically generated electric and magnetic fields [*Mizutani and Ishido*, 1976; *Fitterman*, 1978, 1979; *Ishido and Mizutani*, 1981] result from ion transport in liquids in the direction of fluid flow (see *Fitterman* [1979], *Ishido and Mizutani* [1981], *Morgan et al.* [1989], *Lorne et al.* [1999], and *Ishido and Pritchett* [1999] for descriptions of this process). The distribution of electrical conductivity determines the net far-field magnetic and electric fields resulting from these effects. This is usually incompletely known under volcanoes. The situation for finite flow in limited fault fractures or limited volcanic dikes more closely approximates the case where transient surface electric fields are approximately several tens of millivolts per kilometer [*Fenoglio et al.*, 1995].

The most dominant charge generation mechanism likely near vents, fissures, geysers, etc., is liquid/gas disruption/vaporization effects [*Chalmers*, 1967; *Matteson*, 1971; *Blanchard*, 1964]. This mechanism arises from the sudden disruption of a liquid surface layer under nonequilibrium conditions. The change in properties across a fluid interface leads to a spontaneous charge separation. If this interface is disrupted faster than the charges can adjust, charge transport, or electrification, can result. This separation of charge can be demonstrated in laboratory experiments during rapid boiling from metals and molten Pahoehoe lava. Here water droplets are seen to vibrate rapidly, and minute droplets with a positive charge are seen to be ejected [*Blanchard*, 1964]. For violently boiling water, *Blanchard* [1964] observed a charge production of $10^{-4}$ C/kg of water. Positive charge is also observed when a stream of water breaks into droplets. Ignorance of this effect resulted in explosions on the first supertankers during washdown with high-pressure waterjets [*Pierce*, 1970]. Field observations of electric fields at the base of waterfalls due to this effect are common since early observation of these effects by *Lenard* [1892] and have been termed "waterfall electrification," "Lenard splashing," and "spray electrification." This effect provides the physical basis for Kelvin's famous water drop experiment and Miliken's oil drop experiments [*Loeb*, 1958]. Charge generation by rapid fluid disruption is thus a well-known phenomenon and is not of much concern if this charge is generated in a conducting environment, since it will quickly decay [*Lockner et al.*, 1983]. However, in volcanic rocks where the temperatures at even moderate depths exceed 100° C, resistivity will approach $10^6$ ohm m [*Olhoeft*, 1981]. This charge will not quickly decay and, if continually generated, could produce a quasi-static charged region similar to that observed by *Blanchard* [1964] in the laboratory above hot Pahoehoe lava.

## 3. Laboratory Measurements

The first experiments with fluid injection into hot rocks involved the use of apparatus shown in Figure 2. Fluid (distilled water) was injected into a 0.63-cm (diameter) hole drilled through a 19-cm-long by 7.5-cm-diameter cylinder of Westerley granite. The hole was filled with crushed granite. This apparatus is similar to that used by *Morgan et al.* [1989], *Lorne et al.* [1999], and *Jouniaux et al.* [2000] except that here rock temperatures were maintained at 250° C with an external heater and monitored within the drill hole by using a thermocouple. The potential difference between the top and bottom of the hot dry granite sample was measured with either a digital voltmeter, a digital logger (input impedance 10 Mohms), or a Keithley electrometer (> 100-Mohms impedence). Note that there may be important differences between this experiment, where potential is measured across the hot dry rock sample, and previous EK experiments, where potential is measured within a fluid flowing through the sample. Fluid and gas pressure during and after injection was measured with a ceramic pressure transducer (Setra Systems model 204). Different volumes of fluid could be injected at different rates into the rock and the system sealed after injection with a shutoff valve. Simultaneous observations of pressure, voltage, and temperature were recorded on a 16-bit digital recorder sampling at 200 samples per second. Each experiment was repeated many times to ensure repeatability of results.

As small volumes of room temperature water (~10 $cm^3$) were injected into the hot rock sample, rapid pressure increases and voltage changes occurred before and during fluid vaporization. At the same time, temperature within the simulated crack decreased as the available heat providing water vaporization was removed from the rock. Observations of pressure, potential, and temperature for 15 $cm^3$ of water injected into the sample in 1 second are shown in the top of Figure 3. The expanded section in the bottom of Figure 3 shows pressure and voltage initially increasing as the first water enters the sample. Just under a second later the thermocouple temperature at the point 1.3 cm within the sample starts to fall. Injection ceases at the point of greatest pressure. Initial propagation of steam followed by a rapidly vaporizing water slug generates a positive voltage followed by a negative pulse. Vaporization of the remaining water within the sample then generates a longer-term positive voltage.

Smaller volumes generated proportionally smaller voltages but without the initial negative transient as the water is vaporized within the first few centimeters of the sample and the intake temperature remains above 100° C. Larger volumes quickly decreased the internal rock temperature below the boiling point, and a voltage

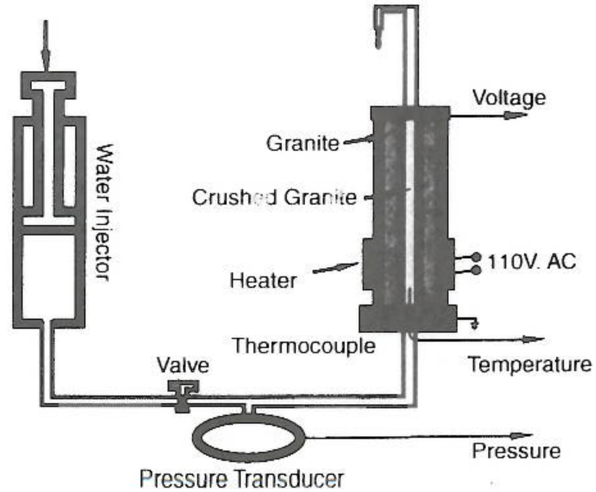


**Figure 2.** Laboratory apparatus used in generating RFD and EK potentials in laboratory rocks.

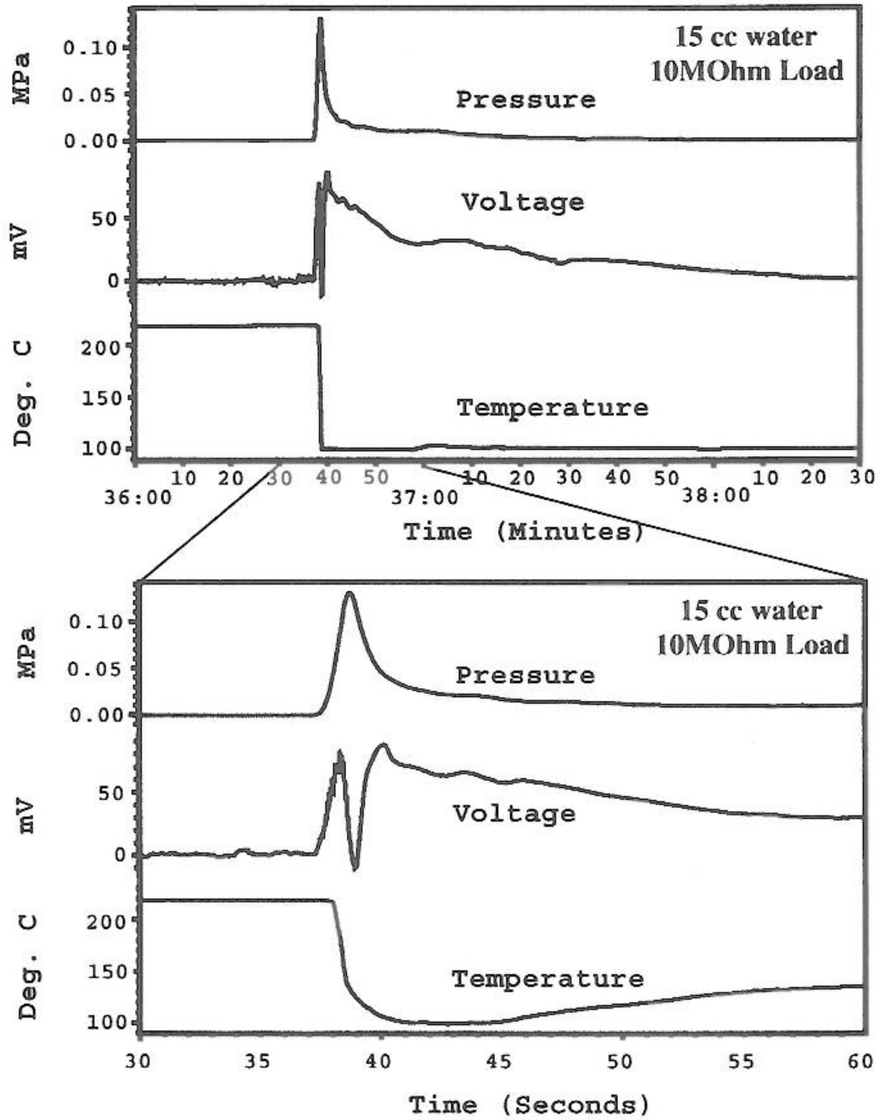


**Figure 3.** (top). Simultaneous pressure, voltage and temperature measurements during injection of 10 $cm^3$ of water into the sample. (bottom). Expanded 30-s section covering the initial phase.

of opposite sign (negative) resulted from simple fluid flow with no vaporization. This is curiously different in sign from that observed within a continuously flowing fluid [*Nourbehecht*, 1963] and observed [*Jouniaux and Pozzi*, 1997] as a result of electrokinetic effects. Figure 4a (top) shows this response when 30 $cm^3$ of water was injected into the sample in 2 s. The expanded view in Figure 4a (bottom) shows an initial small positive voltage as the first steam pulse passes through the sample followed by a negative voltage as temperature throughout the sample is pushed below 100° C.

If, however, this same volume of fluid is injected very slowly into the sample (over 10 s) such that the temperature of the gouge remains above or near boiling, RFD positive voltages again result as shown in Figure 4b (top). The 30-s time period covering the injection is shown in the expanded plot. The initial voltage oscillation and pressure pulse appear to result from nonlinear effects with the first water pulse.

Repeat measurement using the electrometer obtained similar results but higher positive potentials (up to 5 V) due to the higher internal impedence of the electrometer. The amount of charge generated per unit mass of water during these experiments is $\sim 10^{-4}$ C/kg of water. This is similar to that observed by *Blanchard* [1964]. Future experiments are planned using hot basalt and dacite. These can be compared with EK measurements by *Jouniaux et al.* [2000] for fluid flow in cold volcanic rocks. The hot rock experiments should generate similar RFD effects, since *Blanchard* [1964] has already observed similar positive RFD charge generation above hot Pahoehoe lava. The amplitudes of EK effects may vary because of the differences in chemistry [*Lorne et al.*, 1999; *Jouniaux et al.*, 2000].

Other experiments were conducted by using high-pressure gas ($CO_2$) and air in hot dry rock and in both dry and water-saturated gouge in dry rock at room temperature. For the former experiments, results showed

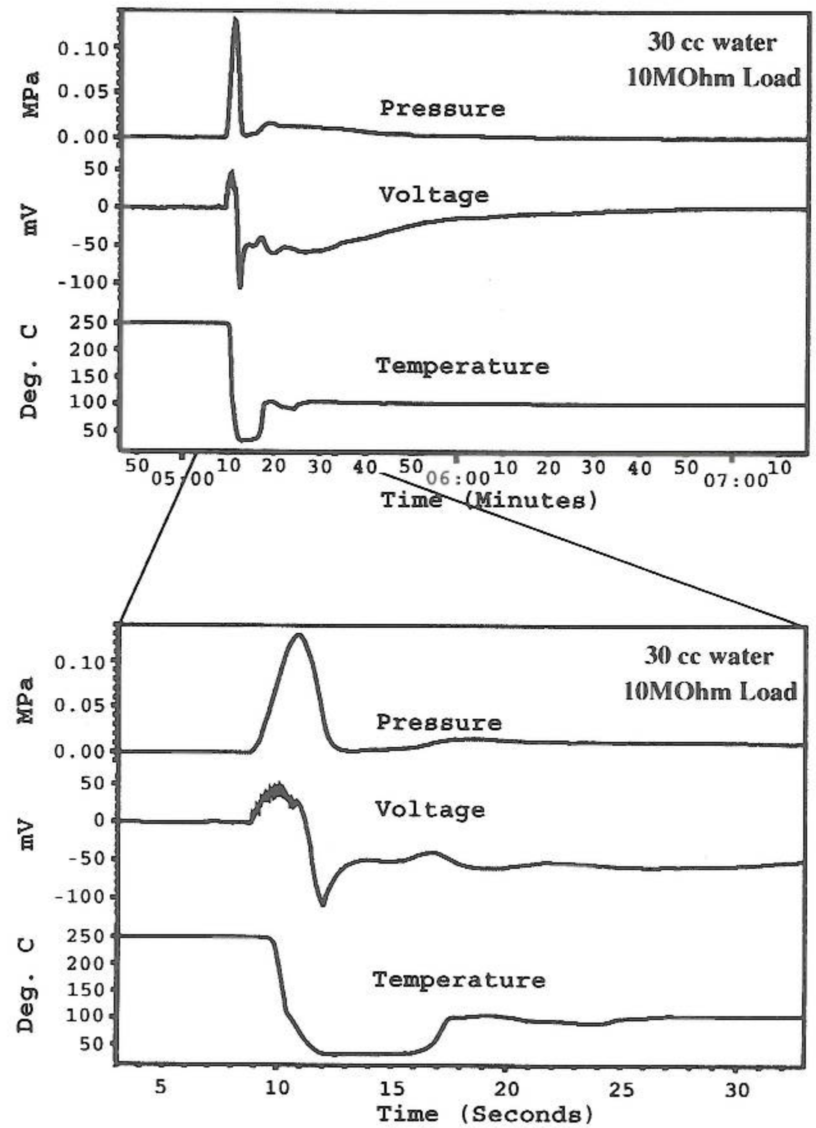


**Figure 4a.** (top). Simultaneous pressure, voltage, and temperature measurements during injection of 30 $cm^3$ of water into the sample. (bottom). Expanded 30-s section covering the initial phase.

that gas flow through hot dry rock generates no significant potential. For the latter experiments, the water input in Figure 2 was changed to compressed gas or air after first saturating the crushed granite gouge in the simulated crack with water while the rest of the rock remains dry. Figure 5 shows increases in voltage and pressure as gas rips water molecules from the gouge and forces them from the rock, thereby forming a mist above the sample. This forced removal of water molecules from the rock generates a positive potential until the rock is dry. Some EK contribution may be occurring also. The slight change in temperature is probably due to adiabatic cooling of the rock. The voltage pulse generated by the gas flow was not at all surprising, since this is similar to the process of charge generation during spray electrification. Spray electrification is a well-known process with a long history (e.g., see *Lenard* [1892]). The important point here is that this process may be pertinent in volcanic regions where significant outgassing is taking place.

## 4. Implications for Field Observations

There are important implications for field observations from these results. Most importantly, *Zablocki* [1976] and *Jackson and Kauahikaua* [1987] observe that all SP anomalies above numerous vents on Kilauea volcano have a positive polarity (see Figure 1 (top) [from *Heliker et al.* 1986]) although some minor negative anomalies were observed in other places. Here the water table is more than 400 m below the surface, and EK effects from near-surface fluid flow are unlikely. The simplest interpretation of this would be that RFD potentials were being generated over the hottest regions, while other regions, where liquids are below their boiling points, are generating EK potentials. This suggests a simple method for identifying the most active/hottest dike activity.

Effects of positive sign were also observed following eruptions on Mount. Unzen, Japan (see Figure 1 (bottom), [from *Hashimoto and Tanaka*, 1995], Piton de la Fournaise, Reunion Island [*Zlotnicki and Le Mouel*, 1990; *Michel and Zlotnicki*, 1998], and Miyake-Jima, Japan (see Figure 6 [from *Sasai et al.*, 1997]. For Unzen volcano, the data set covers only the upper 600-700 m of the volcano. A dramatic increase in SP of over 1000 mV is seen in the 500 m approaching the lava dome generated by the recent activity. The simplest interpretation for the Unzen case is that the primary anomaly is being generated primarily from RFD effects. Furthermore, if RFD charge generation is continuous, as could well be occurring above and around this newly emplaced dome, positive static potentials could remain for some time. EK effects, such as those proposed by *Revil et al.* [1999], could be occurring also, but without information on subsurface flow, it is difficult to quantify these effects. On Miyake-Jima, SP decreased with elevation, as would be expected for an elevation effect [*Corwin and Hoover*, 1979], but went dramatically positive in the summit crater region [*Sasai et al.*, 1997]. After correction for elevation effects, only the large positive anomaly in the recent summit crater remains. Such an effect should be expected from RFD effects.

RFD processes could have detectable effects in the electrical resistivity structure above any hot intrusion in the crater region, changing localized regions from low resistivity ($\leq$10 ohm m) to moderately high resistivity ($> 10^5$ ohm m) but detection of high-resistivity zones in conducting regions could be difficult. Observations of direct resistivity preceding the eruption of Izu-Oshima starting in November 1986 do show increases in apparent resistivity on all three-electrode pairs at different

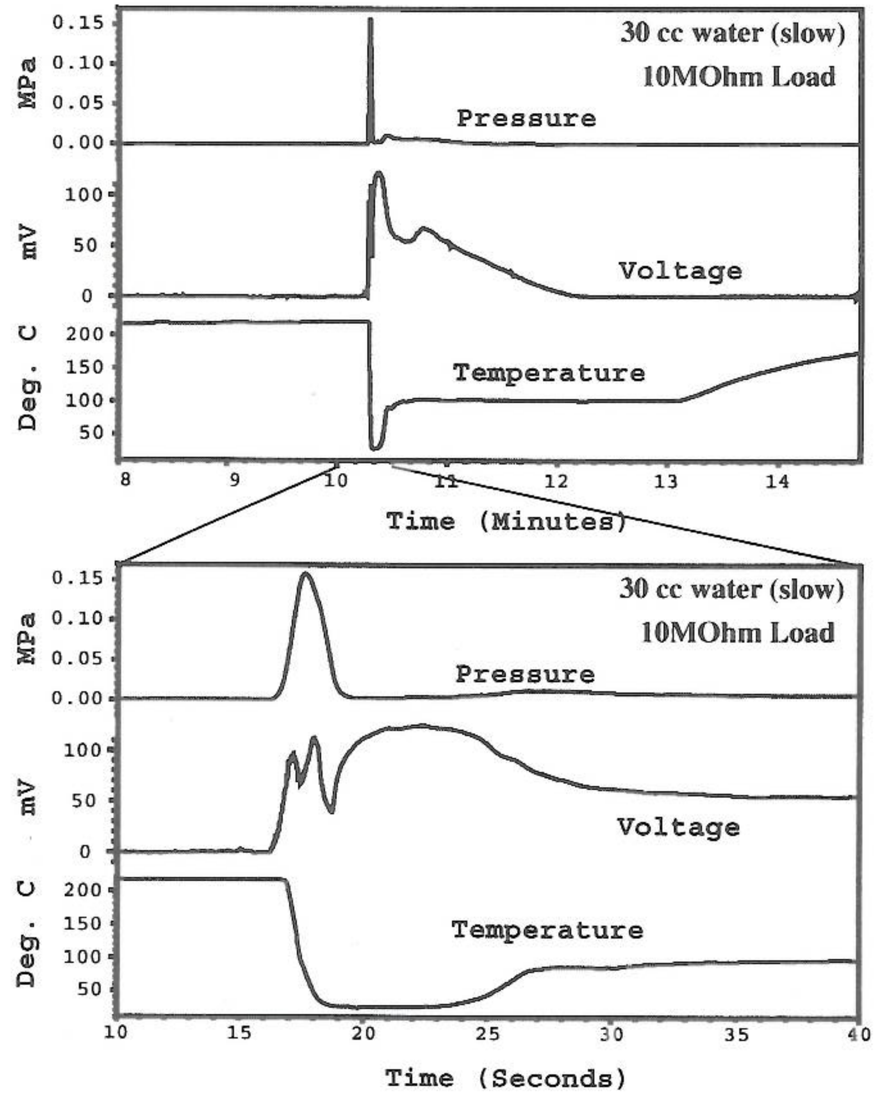


**Figure 4b.** (top). Simultaneous pressure, voltage, and temperature measurements during slow injection of 30 cm$^3$ of water into the sample. (bottom). Expanded 30-s section covering the initial phase.

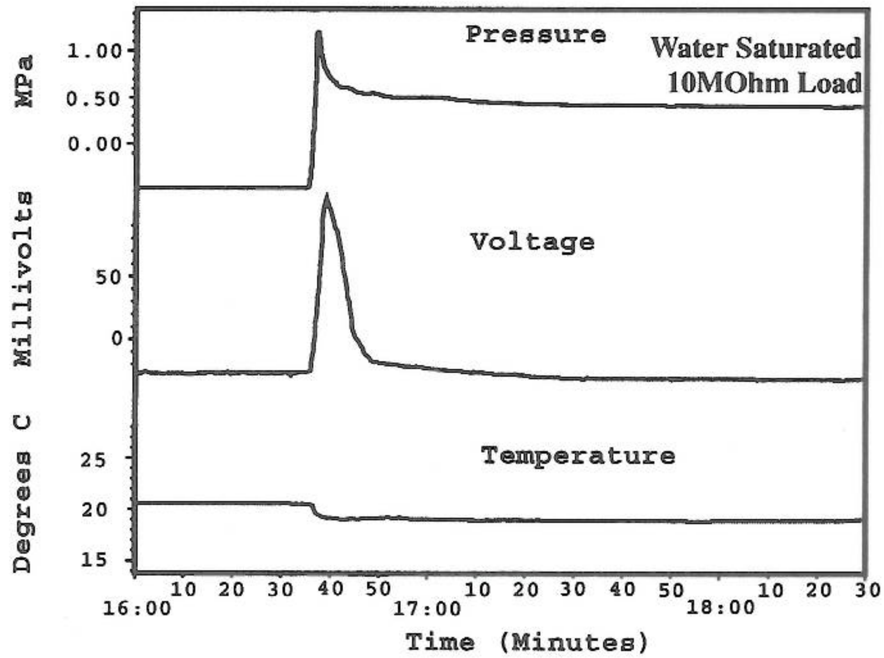


**Figure 5.** Simultaneous pressure, voltage, and temperature measurements during injection of gas into a water-saturated sample.

distances from the crater from January 1986 [*Yukutake et al.*, 1990]. The two closest electrode pairs started to increase much earlier (in July 1985), and by the time of the eruption, the closest electrode pair showed a cumulative 17% increase before its destruction. In contrast, the most distant electrode pair reversed its positive trend in August 1986, and by the time of the eruption on November 15, it showed a 50% reduction in apparent resistivity. *Yukutake et al.* [1990] interpret the increases in resistivity on the close-in electrode pairs as geometric effects. However, resistivity increases as a consequence of fluid vaporization ahead of the magma intrusion might also explain these observations. If so, SP observations in this region should have shown similar time histories. Clearly, simultaneous observations of SP and temporal changes in the three-dimensional electrical resistivity structures are needed to understand these complex processes. More rapid transient-like contribu-

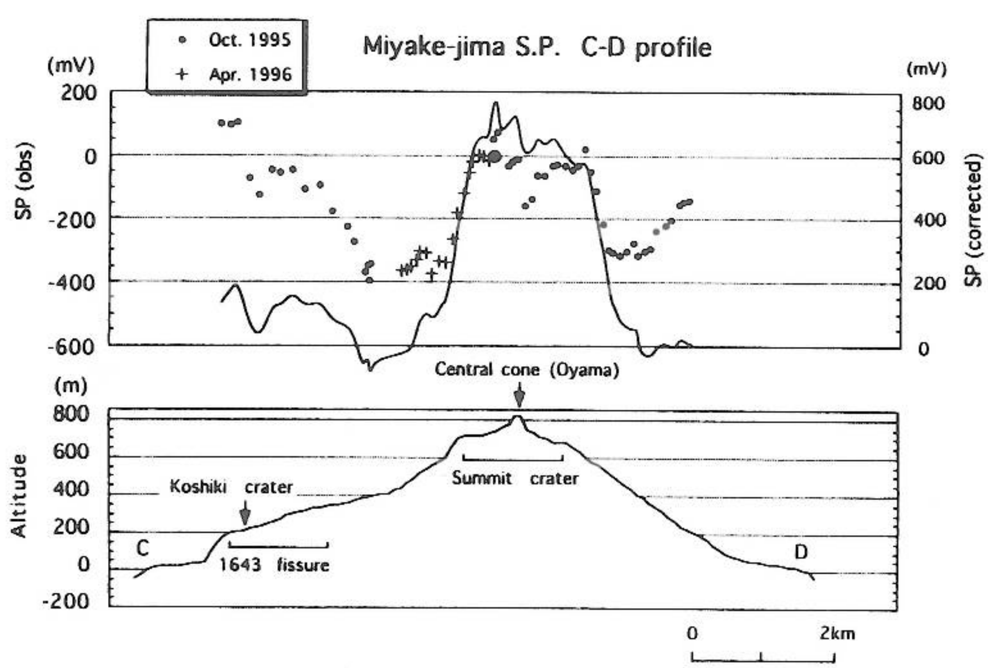


**Figure 6.** Self-potential profile across Miyake-Jima volcano, Japan [after *Sasai et al.*, 1997]). The solid line in the upper plot shows the data corrected for elevation effects.

tions to SP should also be expected during times of activity as high-temperature liquids and gases are rapidly transported during intrusive processes [*Yukutake et al.*, 1990; *Sasai et al.*, 1990] or as liquid/gas oscillations are triggered by the rupture of cracks with associated long-period seismic events [*Chouet*, 1988; *Julian*, 1994] and harmonic tremor commonly observed beneath volcanoes and in geothermal regions.

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