J. Geomag. Geoelectr., **41**, 783–796, 1989

Electric and Magnetic Field Measurements on Mount St. Helens Volcano at Times of Eruptions 1980–1985

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(Received February 7, 1989)

In late September 1980 we installed two continuously recording self-potential lines high on the east flank of Mt. St. Helens volcano. We present here an 8 month record which includes the last of the major explosive eruptions of the series that began with the May 18, 1980 blast. The electric field changes we recorded were less than 0.4 volts on each of our lines for the 8 months. An unusual variation in the electric field occurred on October 12, 4 days before the first explosive eruption of the October series. The longer (1.6 km) line measured a voltage change of 0.4 volts, about twice the amplitude recorded on the shorter (0.6 km) line (0.2 volts). These lines shared a common reference electrode at the point of their highest elevation on the volcano, and both extended radially from the breached crater down the volcano slope. This short-term variation may have been caused by a transient, regional electric field change of scale length greater than 1.6 km that developed on the volcano, having an amplitude of 0.31 volts/km and a duration of about 12 hours. Electrokinetic effects or rainfall are possible explanations for this event. During the explosive eruptions no electric field changes were recorded by our self-potential lines (<0.02 V/km).

In 1981 we added to the magnetic stations already on the flanks of the volcano by installing 4 magnetic stations in the breached crater. The station nearest to the dome was at a distance of 1 km. A magnetic transient was recorded during a dome building eruption in 1981; since no electric field transient accompanied this event and it was associated with extreme nearby strain, we suggest that the magnetic changes were produced by the piezomagnetic effect. During three later time periods, (October–November 83, March–December 84, January–August 85), both the tiltmeters and magnetometers recorded minor variations. These results suggest that the stresses associated with continued dome growth at Mt. St. Helens have become increasingly confined to the immediate vicinity (within 1 km) of the dome.

1. Introduction

In August 1980 we installed two "spiral 4" electric field lines (0.6 km and 1.6 km long) on the east flank of Mt. St. Helens volcano at an elevation of 6000 feet and connected them to high impedance amplifiers; the outputs of the lines were recorded on Rustrack chart recorders. The object was to record changes in the electric field on the volcano over a cycle of inflation, eruption, and deflation. Subsequently, we also measured magnetic fields at 7 sites on the volcano to search for volcanomagnetic effects and for comparison with electric field changes.

Substantial spatial variation in the horizontal component of the near surface electric field of the Earth has been measured in many locations (ANDERSON and JOHNSON, 1976; ZABLOCKI, 1976; ERNSTSON and SCHERER, 1986; JACKSON and KAUAHIKAUA, 1987). In volcanic areas, the variations are thought to be due to the electrokinetic effect which arises from fluid flow having the effect of separating positive and negative charges, giving rise, in some circumstances, to external electric fields measurable at the surface. Little is known about the fluctuations in this field at the time of eruptions. In Hawaii, the near surface electric field is largely insensitive to the eruptive state of the volcano (D. Jackson, personal communication). We believe that continuous measurement has not been made previously on an explosive volcano at the time of eruption. Such eruptions are often associated with extreme buildup of electric fields in the ash cloud, resulting in the generation of lightning. With such rapid mass transport internal electrokinetic effects should occur. We therefore initiated a program to measure the associated variation in ground potential during an explosive eruption.

Although the physics of the electrokinetic phenomenon is well understood, details of the relevant parameters of a volcano, such as conductivity, streaming potential and the fluid flow, are not. Even so, significant change is likely to occur in the flow pattern of ground water in the edifice of a volcano that undergoes inflation due to the intrusion of magma and strain to the point of extensive failure. Such a change in flow regime would in turn generate changes in the surface electric field, which would then give an integrated measure of subsurface strain change and a possible predictor of impending activity.

A further reason for measuring electrokinetic effects on a volcano is the possibility that the magnetic events that have been observed on a number of volcanoes (JOHNSTON and STACEY, 1969a, b; DAVIS *et al.*, 1979, 1984) and some earthquakes (SASAI and ISHIKAWA, 1980; SHAPIRO and ABDULLABEKOV, 1983; JOHNSTON and MUELLER, 1987) are not in fact due to piezomagnetic effects in crustal rock, the favored explanation, but are due to changes in the current flow pattern in the earth. Thus, simultaneous measurement of magnetic and electric fields could, in principle, help to discriminate between "magnetokinetic" and piezomagnetic effects which can occur with or without, respectively, substantial associated electric field changes.

2. The Electrokinetic Effect

Electrokinetic effects are electric currents that flow in the Earth; they are thought to be caused by fluid motion through geologic materials (NOURBEHECHT, 1963; as quoted in FITTERMAN, 1979a, b). It has been suggested (MIZUTANI *et al.*,

1976) that these currents could produce observable magnetic fields, such as the variations associated with the Matsushiro earthquake swarm, which correlated with water outflow from the ground (MIZUTANI and ISHIDO, 1976).

Models of such effects are found in papers by DEWITTE (1948), ROY and CHOWDHURY (1959), MEISNER (1962), PAUL (1965), ANDERSON and JOHNSON (1976), FITTERMAN (1978, 1979a, 1979b), and SILL (1983). Their magnitude depends on the product of the streaming potential, the pressure difference, the electrical conductivity, and flow geometry (FITTERMAN, 1979a). The physical origin of the effect arises from the affinity of ions (generally negative) of like polarity to the rock matrix, whereas ions of opposite polarity are carried along by the fluid flow. Eventually a steady state is achieved, in which the forces of the fluid flow are balanced by the electrostatic restoring force of the clinging charges. The equilibrium position is then displaced in the direction of flow, which gives the region a net polarization. This polarization can give rise to an external field away from the flow when the flow regime contains regions of contrasting polarity due to, for example, contrasting permeabilities. Then, as in the analogous case of magnetostatics, uncompensated poles at the regions of polarization contrast generate the external field. This external field will in turn cause current to flow in the exterior region, depending on its resistance and the internal resistance of the mechanical emf of the electrokinetic generator. The general solution involves taking into account the coupled effects.

On a volcano, one model assumes that the water-saturated zone is in contact with hot intruded rock that sets up a convection pattern below the water table (ZABLOCKI, 1976). Measurements are made at the surface on probes implanted in the vadose zone. Owing to geological heterogeneity, there are discontinuities in the convective flow pattern; for example, a rapid decrease in the permeability with depth due to overburden pressure, which gives rise to uncompensated poles. These produce an electric field in the vadose zone and small current flow. This field can be measured on self-potential lines. Changes in the flow due to extensive ground cracking associated with the inflation of a volcano would cause redistribution of the uncompensated poles. Electrokinetic effects would then correlate with volcanic inflation and deflation. However, there is not complete agreement on the source of the anomalies. Other possibilities include the downward flow of meteoritic water through the vadose zone to the water table and the upward flow of material through the process of evapotranspiration.

As well as flow in the ground, chemical reactions and thermoelectric effects may also be sources of terrestrial electric fields. All such anomalies are termed self-potential (SP) and are well known in exploration geophysics (e.g., TELFORD *et al.*, 1976). They can be particularly large over sulphide bodies. Recent work in Hawaii (ZABLOCKI, 1976; JACKSON and KAUAHIKAUA, 1987) has established that large SP anomalies occur on Kilauea volcano, Hawaii. The anomalies may be separated into two categories: long wavelength which exhibit an apparent inverse correlation with topography (the topographic effect, TE, ERNSTSON and SCHERER, 1986) and shorter wavelength anomalies which have been interpreted as being due to localized intrusion of volcanic material. JACKSON and KAUAHIKAUA (1987) report that the TE anomaly correlates better with the thickness of the vadose zone than with topography. They suggest that the TE effect is due to percolation of ground water through the vadose zone to the underlying water table.

The shorter wavelength anomalies in Hawaii are attributed to hydrothermal activity due to the intrusion of volcanic rock. The rising fluids produce electrokinetic potentials and would also thin the vadose zone. ERNSTSON and SCHERER (1986) consider electric effects associated with the vertical transport of matter by evapotranspiraton through the vadose zone.

Although the detailed mechanism for generating SP anomalies in volcanic areas is uncertain at this stage, there is general agreement that it involves the mechanical transport of matter through the Earth. Also, calculations based on hydrogeological models confirm that this mechanism is adequate to generate the remarkable anomalies that are seen to persist at the surface.

Short wavelength anomalies in Hawaii can be as high as 1.5 volts over 0.5 km. Measured resistivities of 1000–10,000 ohm-m in the region imply that currents of milliamps/m^2 are flowing, though this is dependent on geometry. Thus, intrusive changes in a volcano as well as ground deformation should disturb the flow of the streaming potentials sufficiently to produce measurable temporal variation in localized electric field and, possibly, magnetic anomalies at the surface.

3. Electrokinetic Monitoring of Mt. St. Helens

When it appeared after the May 18, 1980 explosive eruption of Mt. St. Helens that the volcano was going to keep erupting, and there appeared to be evidence accumulating that the ensuing eruptions were associated with localized magnetic activity (JOHNSTON *et al.*, 1981), we decided to test whether the magnetic changes were correlated with near surface electric field changes. We installed two SP lines radially out from Nelson's ridge, a point at 6000 ft elevation on the east flank of the volcano at the same elevation as the central vent and 1 km from it. Station locations are shown in Fig. 1. The electrodes consisted of copper ("weld") rods sunk into post holes dug six feet into the volcanic ash. A wetted salt and ash mixture was used to fill the holes to achieve good electrical contact and also to minimize local chemical emf's. Voltages were measured relative to a common electrode at the highest elevation. The system was powered by Air Cells and recorded onto two Russtrack recorders with coarse (2 V) and fine (200 mV) ranges. It survived about two years and we have records during the last of the explosive eruptions of 1980 (16–18 October) and during some extrusion events in 1981 when we also recorded magnetic fields in the crater of the volcano (DAVIS *et al.*, 1984).

4. The October 1980 Eruptions

The October 1980 eruptions (Table 1) were the last major explosive eruptions of the volcano prior to going into its dome-building phase. The first occurred on

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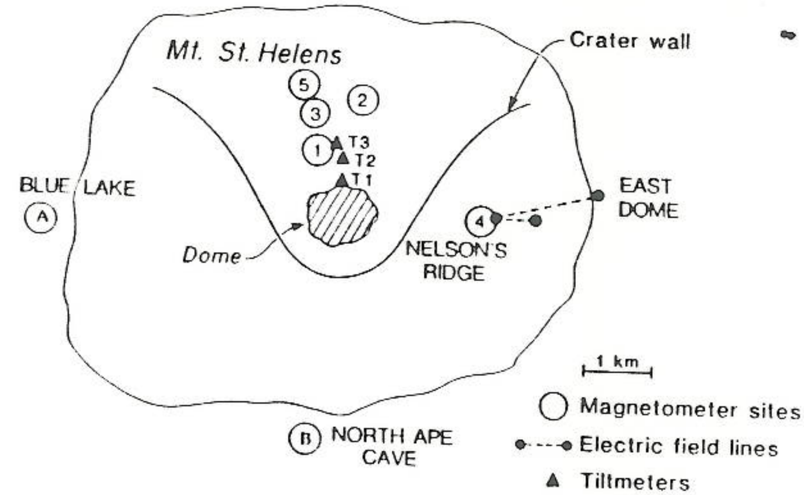


Fig. 1. Map of locations of 2 self-potential lines installed on Mt. St. Helens to search for electrokinetic effects at the times of the eruptions of the volcano. Locations of magnetometers 1–5 and A and B are also shown.

Table 1. Eruptions of Mt. St. Helens at the times of magnetic and electric recording.

Date	Eruption type
Oct. 16 1980	Pyroclastic
Oct. 17 1980	Pyroclastic
Oct. 17 1980	Pyroclastic
Oct. 18 1980	Pyroclastic
Oct. 18 1980	Pyroclastic
Dec. 27 1980	Dome Building
Feb. 2 1981	Dome Building
Mar. 27 1981	Dome Building
Oct. 24 1981	Dome Building
Mar. 29 1984	Dome Building
May 14 1984	Small Explosion
Jun. 28 1984	Dome Building
Sept. 4 1984	Dome Building
May 17 1985	Dome Building

October 16 at 9:58 p.m. Pacific Standard Time (PST), sending a cloud of pyroclastic material to a height of about 44,000 feet. Two additional eruptions occurred on October 17 at 9:28 a.m. and 9:12 p.m., sending ash clouds to 47,000 and 45,000 feet respectively. These were followed by eruptions on October 18 at 12:23 p.m., 12:45 p.m., and 14:28. This activity was followed later in the year by a series of dome-building extrusive eruptions which began on December 27, 1980 (DECKER, 1981) with events on February 2 and March 27, 1981.

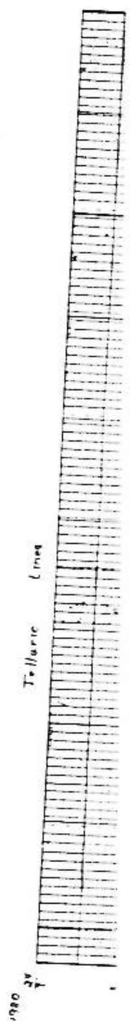
5. Results

Figure 2 is a photograph of the Russtrack record for the electric field lines at Nelson's Ridge from October 1, 1980 until December 31, 1980. The solid trace is the record for the 1.6 km line and the dotted trace is the record for the 0.6 km line. A digitized version of both records and the precipitation at nearby Cougar is seen in Fig. 3(a). An expanded version of the October transient is shown in Fig. 3(b) with the times of the explosive eruptions marked.

The most significant feature in the record is the transient which occurs on October 12. A perturbation was observed on both lines but it was greater on the longer line, having an amplitude of about 0.4 volts. It initially swings negative, then recovers with a large positive excursion which decays over the next few days. The shorter line shows a smaller correlated event but without the initial negative excursion. Other notable excursions from the baseline include the event beginning on about November 1 and a positive anomaly which begins about December 18 and returns to the baseline January 12. The latter period roughly corresponds to a time of renewed dome activity which began with an explosion on December 13–14, followed by a seismicity increase on December 25 and dome growth December 28–January 4 (DECKER, 1981). However, this also corresponds to a period of precipitation (Fig. 3(a)).

Figure 3(b) shows that the electric field anomaly is not associated with the times of the explosive eruptions themselves, preceding them by several days. However, the fact that the perturbation was seen on both lines with amplitude roughly proportional to line length, provides some evidence that the phenomenon was large scale, i.e., not localized to self potential effects at one of the sensors but a regional electric field change.

We have not identified any other geophysical records at the time that correlate with this electrical event other than in a very broad sense. The data we have investigated include trilateration, seismicity, tilt, the magnetic field gradient between Blue lake and North Ape Cave (JOHNSTON *et al.*, 1981) and degassing observations. It was a period of extreme tumescence. The micro-seismicity was high the week before the eruption (DECKER, 1981); the period corresponds to the end of a significant inflation of the volcano (SWANSON *et al.*, 1981) of over 150 μ strain since June 1. Degassing was intense and cracks were opening in the crater prior to the eruption (as shown by SWANSON *et al.*, 1981). The degassing consisted of gas discharges from the vent which were severe enough to contain small ballistics (Don Swanson, personal communication). The degassing period is represented in Fig. 3(b) as the hatched region. Unfortunately, the detailed continuous monitoring needed to correlate the degassing and electric field changes is not available. Part of the reason for this was the bad weather with high rainfall which began late on the night of October 11, i.e., about the time of the initiation of the electric field anomaly.



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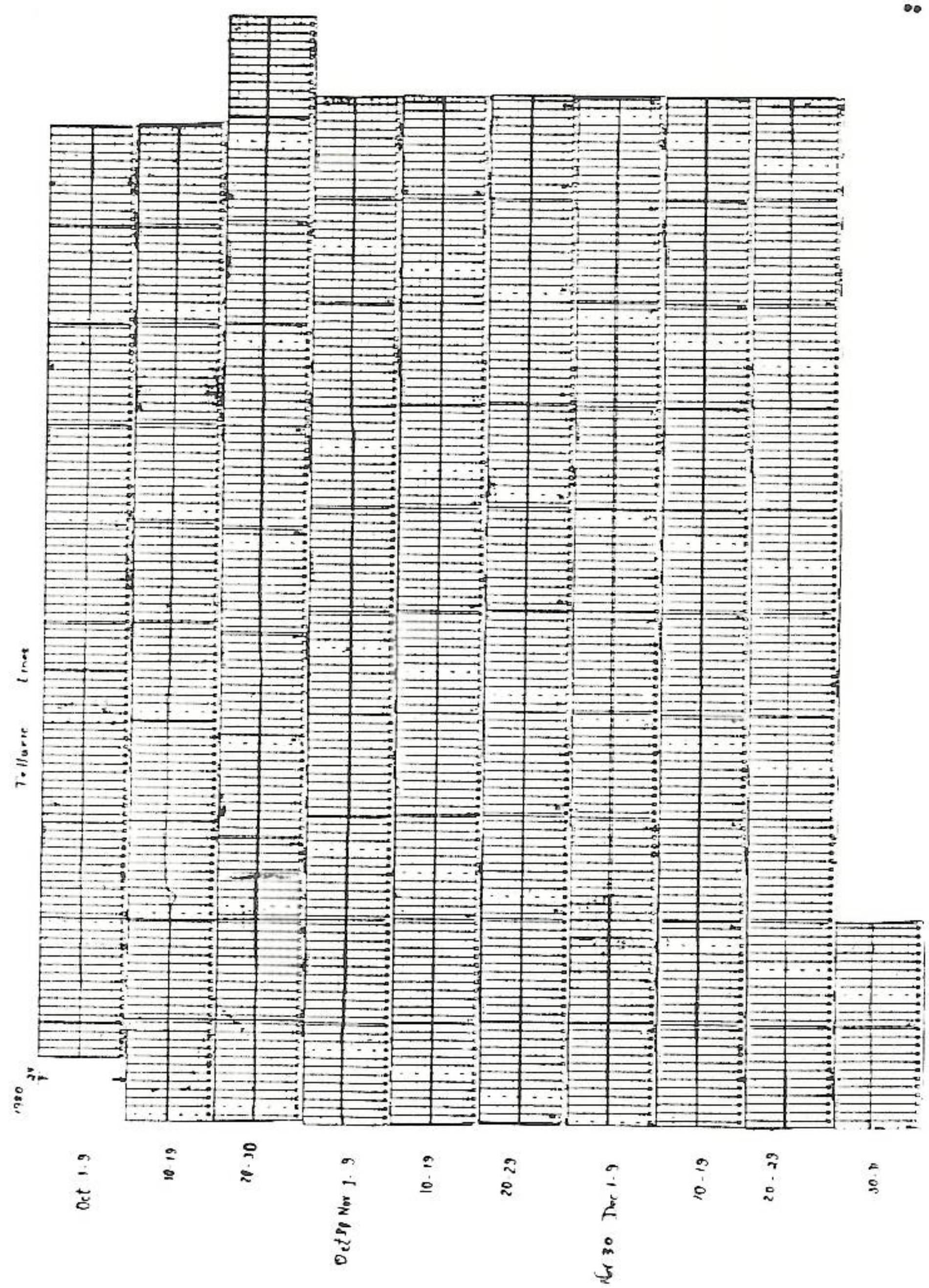

Fig. 2. Photograph of 6 months records for the 2 self-potential lines of Fig. 2. The solid line is the voltage on the longer (1.6 km) line, the dashed line is that for the shorter (0.6 km) line. A transient occurs on October 12, 4 days before the last major explosive eruption of the volcano. However, at the times of the eruptions negligible effects occur.

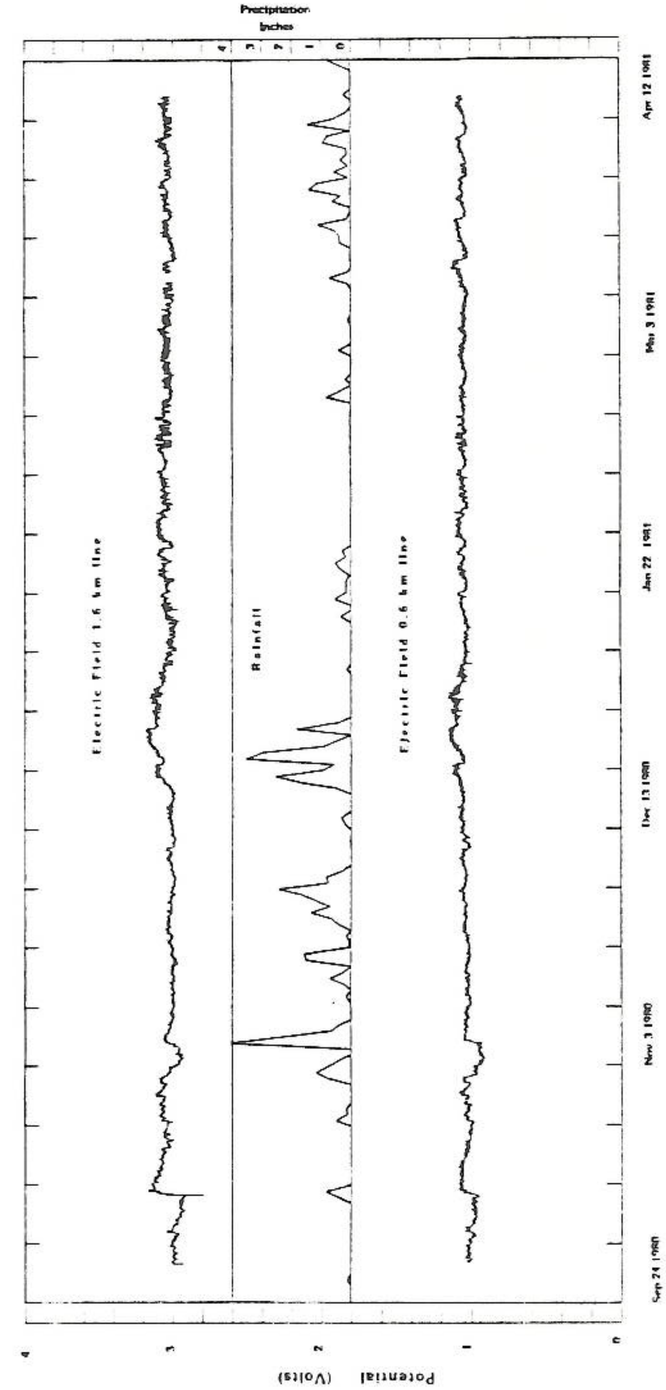

Fig. 3(a). Digitized version of Fig. 2 showing the time of the October eruptions and a dome building eruption in late 1981. The daily rainfall record at Cougar, 15 km away, is also plotted.

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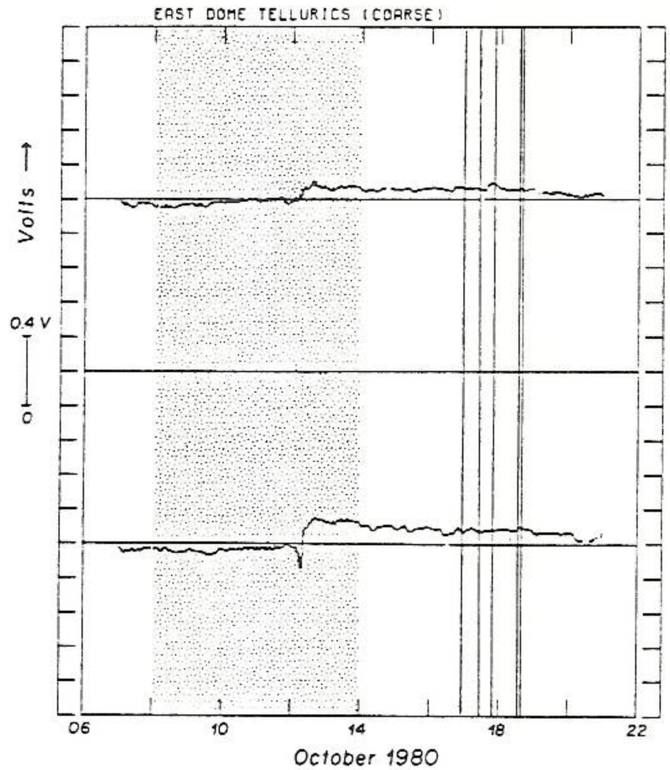

Fig. 3(b). Expanded plot of the October electric field transient showing the period of enhanced degassing of the volcano (hatched region taken from SWANSON *et al.*, 1983) and enhanced seismicity. Vertical lines denote explosive eruptions.

6. Rainfall

We checked to see if rainfall could explain the observation. A plot of rainfall measured at Cougar, 15 km away, (NOAA Climatological Data Precipitation Summaries, Washington) (Fig. 3(a)) shows that while it did indeed rain in the area on this day, there are periods of even greater rainfall on other days throughout the period which did not produce proportionately greater effects. However, it was the most significant rainfall since installation and could possibly represent a settling-in effect of the electrodes. Also, after about November, what was measured as rain at Cougar would precipitate as snow on the volcano. This could account for a different response in the winter months; therefore, the relevant comparison is for the same period the year after. However, there is no electric field event like it or the other transients in the record (such as those of November 1 and December 18–January 12) in the whole record for 1981, which all looks similar to the flat behaviour of the latter months of Fig. 2. Thus the response to rainfall must have changed significantly if that is the preferred explanation for the October 1980 transient.

7. Correlation with Magnetic Fields

Magnetic fields were continuously recorded by the U.S. Geological Survey at Blue Lake and North Ape Cave during the October 1980 eruption (JOHNSTON *et al.*, 1981). The record shows no transient changes associated either with the eruption or the electric events we measured. A year later, in 1981, we installed 4 magnetic stations in the crater in a region beginning 1 km north of the Dome and extending north, and one station on the east flank (Fig. 1). Records are intermittant from this extremely hostile environment, where keeping the instruments continuously recording was hampered by deep coverage of snow in the winter as well as equipment loss due to eruptions and mud flows. In 1982 the equipment was refurbished and recording resumed in 1983. A summary of the daily averages of the magnetic difference fields we measured is seen in Fig. 4. We have reported elsewhere (DAVIS *et al.*, 1984) a magnetic transient observed in October 1981 which we attributed to piezomagnetic effects in the volcanic rock. This transient was accompanied by extreme tilts on the floor of the crater. However, on the flank at Nelsons Ridge, where the electric sensors were located, the electric field remained essentially constant (see Fig. 2, DAVIS *et al.*, 1984). We have observed no such magnetic transients since this event in all the data recorded. However, nor have there been any repeat episodes of such extreme tilting at these locations associated with the numerous dome building eruptions that have ensued. The strain field, which back in 1981 extended well away from the dome into the crater floor, subsequently became confined to the vicinity of the dome. Thus, the combination of decreased activity and contraction of strain transients to the dome area has resulted in an absence of magnetic transients measured at these sites and can account for the lack of further electric field effects after those of late 1980.

8. Discussion

The 0.4 volt transient change in the SP anomaly seen on October 12 is a unique event of much larger amplitude than has been previously observed. ERNSTSON and SCHERER (1986) observed a correlation between precipitation and SP anomaly measured over a 200 m distance in Buntsandstein, W. Germany, which lagged the precipitation record by 1 month. They state that "even after heavy storms, with exceptionally high precipitation, an immediate reaction of the TE was not observed." Similar insensitivity to heavy rain has been observed in Hawaii (Dallas Jackson, personal communication).

If it was not caused by rain, the alternative explanation that intense stressing of the volcano actively changed the electrokinetic emf is plausible, but independent correlation with the form of the electric signal in records such as tilt or micro-seismic activity is lacking. The time period of the signal is a period of strong degassing, enhanced seismic activity and extreme inflation, but this activity has not been observed in sufficient detail to show correlation.

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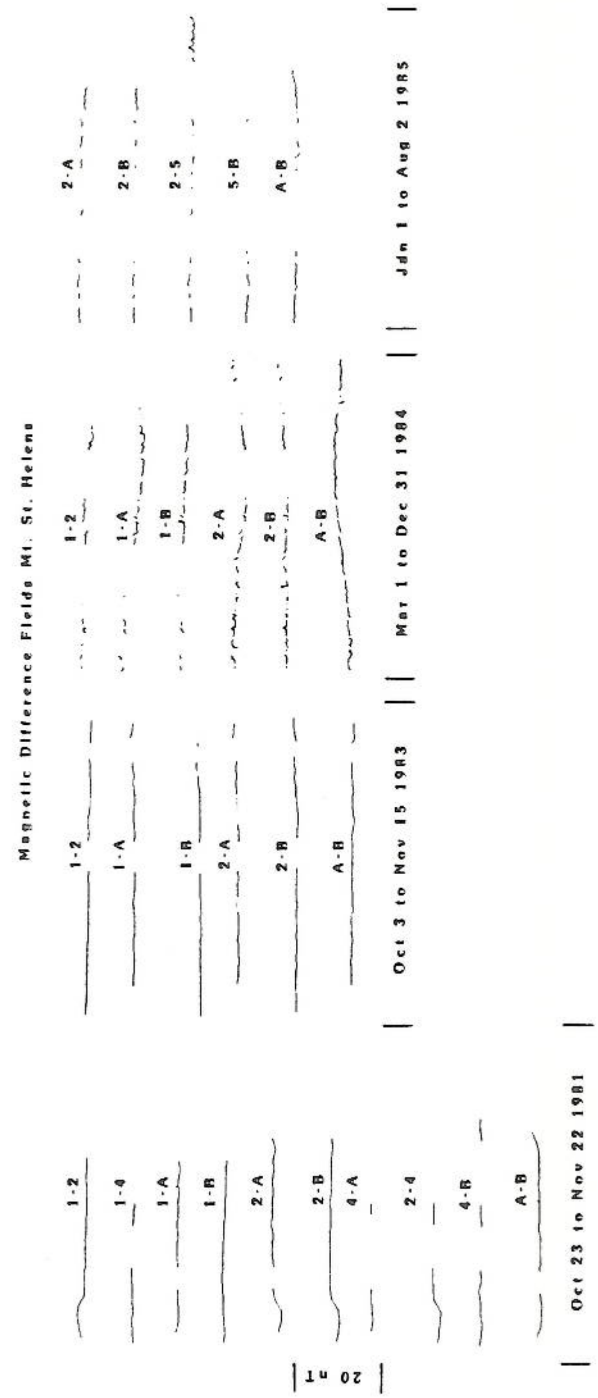

Fig. 4. Summary plot of differential magnetic field measurements for the period 1981–1985 illustrating that the October 1981 transient magnetic event was a unique occurrence. No such anomalies were seen subsequently. This is consistent with the fact that, with time, crater tilt strain decreased in amplitude and concentrated near the dome, i.e., out of the measurement region of the magnetometer array.

During this period of the volcano's activity, extreme strains were observed well away from the summit, whereas subsequently the strain has confined itself to the immediate vicinity of the dome. The electric field lines were probably in the near field of intense straining in 1980 and less so in 1981, which could explain the reduced electrical activity with time. Possibly the combination of rainfall and degassing of an extremely inflated volcano just prior to eruption provided conditions which were unique at this time, whereas a year later the flanks were less inflated, cracks less open and, as a result, the volcano flank less permeable.

9. Conclusion

We are left to surmise that we have observed regional (1 km) transient changes in the self-potential field on Mt. St. Helens volcano. The largest was possibly related to the rainfall at the time and the intense straining of the edifice during a period of strong degassing late in 1980 prior to the October eruptions. It has not been possible to decouple rainfall effects from internally generated volcanic effects.

Arguments in favor of rainfall effects only include the fact that there is a fairly good correlation between the onset of the October electric event and the rain record; it was the first major shower since installation. Other electric events in early November and mid December occur at times of high precipitation (Fig. 3). Arguments against the rainfall-only explanation include the fact that a number of even stronger rain showers occurred later in 1980 and in 1981 which did not produce similar effects. Also such a large immediate response to rainfall has not been observed either in Germany or Hawaii, where comparable measurements have been made.

Arguments for the alternative origin of the effect, internally generated electrokinetic changes, include the observation that the strain in the vicinity of the station had built up to near the breaking strength of rock. The volcano was strongly degassing and micro-seismicity was high. Arguments against include the observation that there are no detailed correlations with any of the other geophysical parameters measured on the volcano.

Given the uncertainties, what can be learned from these data? We believe these are the first measurements of the electric field on the flanks of a volcano at the time of an explosive eruption. As can be seen in Fig. 3(b), at the instant of eruption the field remained steadily decreasing, in spite of the substantial mass flow through the throat of the volcano. Such pyroclasic eruptions have been known to generate the high voltages necessary to produce lightning in the eruption cloud. We can limit the electric field changes in the earth for the October 1980 eruptions to less than 0.02 volts/km (the thickness of the line in Fig. 3(b)) at the time of eruption; for the entire 1.25 year record, the maximum electric field changes were no greater than 0.31 volts/km, i.e., those seen just before the explosive eruptions.

The October 1981 magnetic event is unique in the records from the crater floor. It was not accompanied by an electric field change at Nelson's ridge. Lack of further changes in the magnetic field is consistent with the observation that as the volcano's activity waned, the transient strain field associated with eruptions has contracted to the immediate vicinity of the dome, whereas in 1980 and 1981 it extended more than 1 km from the dome where it generated the observed piezomagnetic effect and electric effects which were probably electrokinetic in origin.

This work was supported by NSF grants EAR 82-18614 and EAR 85-46072.

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