Bull Volcanol (1992) 54:590-594

Bulletin of Volcanology

Electric potential gradient changes during explosive activity at Sakurajima volcano, Japan

SJ Lane and JS Gilbert

Department of Geology, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ

Received October 9, 1991/Accepted March 11, 1992

Abstract. We report electric potential gradient measurements carried out at Sakurajima volcano in Japan during: (1) explosions which generated ash plumes, (2) steam explosions which produced plumes of condensing gases, and (3) periods of ashfall and plume-induced acid rainfall. Sequential positive and negative deviations occurred during explosions which generated ash plumes. However, no deflections from background were found during steam explosions. During periods of ashfall negative electric potential gradients were observed, while positive potential gradients occurred during fallout of plume-induced acid rain from the same eruption. These results suggest that a dipole arrangement of charge develops within plumes such that positive charges dominate in the volcanic gas-rich top and negative charges in the following ash-rich part of the plume. The charge polarity may be reversed for other volcanoes (Hatakeyama and Uchikawa 1952). We suggest that charge is generated by fracto-emission (Donaldson et al. 1988) processes probably during magma fragmentation within the vent, rather than by frictional effects within the plume.

Introduction

The potential difference between two points is the mechanical work per coulomb needed to move a small positive charge from one point to another (Chalmers 1967). If a positively charged body is moved from a point at a lower potential to that at a higher potential (i.e. in the direction of increasing potential), then a positive amount of work is done, so that the body is moved against a force. The ratio of the force acting on the body to the charge on the body is known as the electric field. The direction of the electric field is therefore opposite to that of the rate of change of electric potential, or electric potential gradient. The convention used is that the positive direction is upwards from the surface of the Earth (Chalmers 1967). Since the surface of the Earth is a conductor, it follows that the lines of force must reach the surface in a normal direction. Thus, where the Earth's surface is horizontal, the lines of force are vertical to the surface and the potential gradient (rate of change of potential with height) is vertical.

In fine weather, when there are no atmospheric clouds for hundreds of kilometres, there is a weak electric field of the order of $-120\ \mathrm{V\ m^{-1}}$ at the surface of the Earth (Iribarne and Cho 1980). Soundings made from balloons and aircraft show that the fine-weather atmospheric electric field decreases (in absolute value) with altitude until it essentially disappears, approaching the highly conducting part of the atmosphere known as the ionosphere.

All atmospheric clouds produce electrical perturbations because their electrical properties are different from those of clear air. In general these perturbations are so small that it is impossible to recognise the external electric fields of clouds against the normal variations of the electric field in the surrounding cloudless atmosphere. The exception to this is the thundercloud, which is capable of producing electric fields sufficiently large to result in electric sparks many kilometres in length, which we recognise as lightning. Thunderclouds are characterised by convective instability with strong updrafts and downdrafts. Measurements of electric potential changes beneath and within thunderclouds suggest that most have a concentration of positive charge in their upper regions, with a lower region of negative charge (Chalmers 1967). Frequently there is a further concentration of positive charge in a limited zone at the base of the cloud. This arrangement is thought to be the result of gravitationally driven charge separation processes operating at different levels within the cloud (Chalmers 1967).

Charge distributions have also been described in non-raining clouds (Whitlock and Chalmers 1956) and in dust devils (Freier 1960; Crozier 1964). Electric potential gradient measurements made during fair weather, beneath clouds, during rainfall and snowfall, and at the coast (where breaking waves produce space charges which effect the fine-weather potential) are available

Correspondence to: JS Gilbert

(Chalmers 1967). Positively and negatively charged particles in a volcanic plume can carry sufficient charge to cause attraction between particles and form ash clusters (Gilbert et al. 1991). However, the way charged particles and ions are distributed within volcanic plumes is not well understood and electric potential gradient data are scarce for eruption plumes. Hatakeyama and Uchikawa (1952) interpreted the plume of Aso volcano, Japan in 1950 to be dominated by positive charge in its lower and negative charge in its upper region. Electric potential gradient measurements made during the eruption of Surtsey in 1964 (Anderson et al. 1965) found the plume to be dominated by positive charge in its upper and negative charge in its lower region, the converse of the Japanese work at Aso. None of the volcanic studies investigated the effect of plume-induced acid rainfall on the potential gradient.

The volcano

Sakurajima volcano is an andesitic strato-volcano in southern Kyushu, Japan. It is situated on the southern rim of the Aira caldera which occupies the northern part of Kagoshima Bay and has had repeated flank and summit eruptions during historic times (Ishihara 1990). Since summit eruptions, typically of vulcanian style, have occurred on an almost daily basis since 1955 Sakurajima is a reliable 'working laboratory' for volcanic plume experiments. The volcano is continuously monitored by the Sakurajima Volcanological Observatory scientists of Kyoto University.

From seismic and infrasonic work Sakurajima's eruptions have been classified into three types (Ishihara 1990). These are: (1) explosive eruptions (vulcanian style); (2) non-explosive eruptions; and (3) continuous eruptions. During explosive eruptions atmospheric shock-waves and explosion earthquakes (Ishihara 1985) commonly accompany the generation of short-lived (i.e. for periods of hours) either ash-laden or steam plumes which rise to heights of <5 km above the vent. Continuous eruptions are seismically identified by swarms of micro-earthquakes (Kamo and Ishihara 1989) and accompany the generation of long-lived (i.e. for periods of days) ash-laden plumes. Sakurajima's plumes are commonly influenced by the wind and deposit ash asymmetrically around the active vent (Minamidake) on the surrounding countryside, villages and Kagoshima city.

The experiments described in this paper were carried out in March, April and May 1991 during explosive eruptions which generated both steam and ash plumes. The plumes rose to a maximum of 3 km above the vent and deposited ash for periods of less than 2 h, at distances greater than 2 km from the vent.

Experimental approach

At Sakurajima vertical electric potential gradient measurements were made 2–5 km from the vent using a stationary, tripod-mounted, earthed John Chubb electrostatic fieldmeter (JCI 111). This instrument modulates the electric potential detected at a metal electrode by means of a rotating chopper (Chubb 1990). The resulting signal is related to the magnitude of the electric potential gradient at the sensing aperture and is displayed on a digital readout. In the field the height from the tripod base to the measuring aperture of the fieldmeter was 1.55 m. The advantage of using the tripod was to provide noise-free amplification of the signal (measured to be a factor of 20) in order to overcome increased meter noise levels due to aperture and earth connection contamination. Data presented here have been corrected to ground-level potential gradients. As well as measuring the potential gradient during explosive eruptions, the ambient atmospheric potential gradient was monitored during periods of volcanic quiescence in order to characterise the effects of various meteorological phenomena. During all experimental runs the ambient temperature, relative humidity and percentage of meteorological cloud cover were continuously monitored.

Results

Figure 1a shows electric potential gradient data collected during an experiment at a locality 2.75 km SSE and downwind (on-axis) of the active vent. During the experiment the weather was fine with no cloud cover and there was a slight breeze. For the first 206 min of observation Sakurajima erupted mainly white plumes of condensing gases which rose approximately 300 m above the vent. Occasional ash plumes of similar size were generated which gave rise to very light ashfall. Vent noise was restricted to silence or low rumblings. At 206 min a loud detonation was heard (followed by metre-sized bombs being ejected from the vent) after which a dark ash-laden plume ascended to a height of 3 km and formed a laterally spreading gravity current. Six minutes after the explosion fallout of <1 cm diameter particles commenced.

Data for another observed explosion are seen in Fig. 1b, for an experiment run at a locality 2 km SW of the vent. At the time of the explosion the wind direction was NNW and therefore the locality was off the plume dispersal axis. During the experiment, prior to the explosion, the cloud cover was 0–20% and there was a slight breeze. For the first 82 min Sakurajima was erupting white plumes of condensing gases which rose to a height of 200 m above the vent. After 82 min a loud detonation was heard, at which time a dark ash-laden plume ascended 1.5 km from the vent before spreading out laterally. No ashfall occurred at the measurement locality.

Figure 1c shows the effect on the potential gradient of an explosion which generated only gases. The experiment was run at a locality 2.75 km SSE and downwind of the vent. Prior to the explosion there was a gentle breeze and no cloud cover. During this time Sakurajima was erupting white plumes up to 150 m high of condensing gases and low rumblings were coming from the vent. After 159 min a loud detonation was heard after which a white plume rose approximately 1.5 km from the vent before spreading laterally and dissipating in 15 min. No ash was observed to fall from the plume.

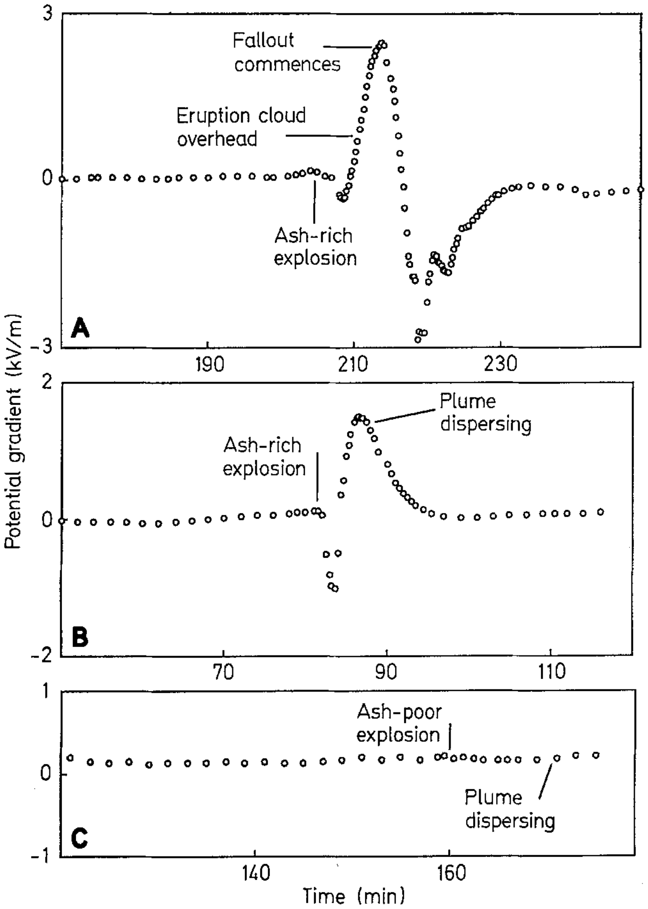

Fig. 1. Potential gradient versus time for three explosive events. **A** Explosion at 13:39 (local time = GMT + 9 h) on 3 May 1991. Temperatures and relative humidities at the start and finish of the experiment were 18° C, 45% and 21° C, 39% respectively. **B** Explosion at 10:16 on 30 April 1991. Temperatures and relative humidities at the start and finish of the experiment were 16° C, 66% and 19° C, 58% respectively. **C** Explosion at 15:44 on 30 April 1991. The temperature and relative humidity half an hour into the experiment were 22° C and 54% respectively

Figure 2 shows the effect of ashfall on the potential gradient. The data were collected at a locality 3.5 km E and downwind of the vent at a time when there was approximately 20% cloud cover and a breeze. During the first 180 min of the experiment white plumes of condensing gases <300 m high were erupted intermittently at which time the volcano was either silent or rumbling. After 180 min a weak detonation was heard and an ash-laden plume ascended approximately 500 m above the vent. Light ashfall commenced 39 min later.

The effect of plume-induced acid rain on the potential gradient was investigated in an experiment (Fig. 3) carried out at a locality 2.25 km NW and downwind of the vent, on an overcast day. Sakurajima was erupting a plume (<300 m high) and rumblings were coming from the vent. A light fall of mainly ash clusters (<2 mm diameter) occurred for the first 30 min of the experiment. Between the periods 15–22 and 32–41 min gentle ash-free liquid drops (which irritated the skin) fell. These drops were tested with Whatman Full Range pH 1–14 paper and found to have a pH of <1. The drops were generated by condensing volcanic gases.

Discussion

The potential gradient data are consistent with ash falling from the plume with an average (sum of positive and negative charges) negative charge (Fig. 2) and plume-induced acid rainfall with an average positive charge (Fig. 3). Explosions which generated no ash produced no measurable fluctuations in the potential gradient (Fig. 1c). Explosions which generated abundant ash were characterised by large changes in potential gradient (Fig. 1a, b). This implies that lava dome rupture during gas-dominated explosive eruptions (Ishihara 1985), does not necessarily generate large amounts of ash or result in significant charge generation. Processes which generate considerable quantities of ash, such as degassing and

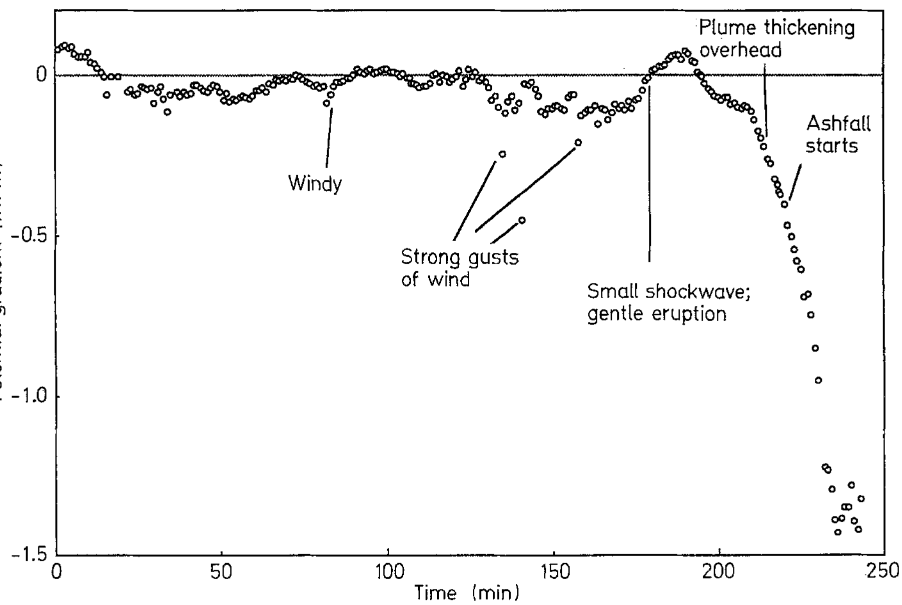

Fig. 2. Potential gradient versus time during ashfall on 25 March 1991. Temperatures and relative humidities at the start and 90 min into the experiment were 24° C, 69% and 24° C, 73%, respectively

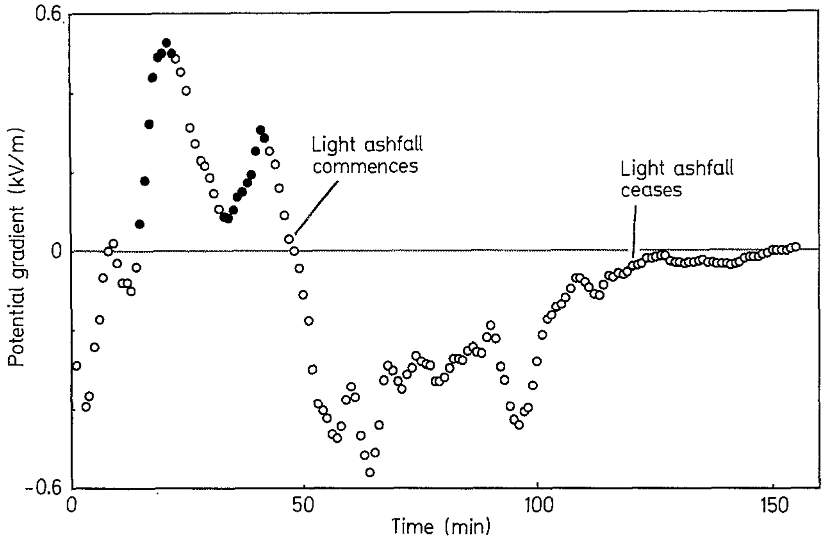

Fig. 3. Potential gradient versus time during acid rainfall on 27 April 1991. At the start and finish of the experiment temperatures and relative humidities were 16° C, 90% and 19° C, 74% respectively. *Solid symbols* indicate periods of plume-induced acid rainfall

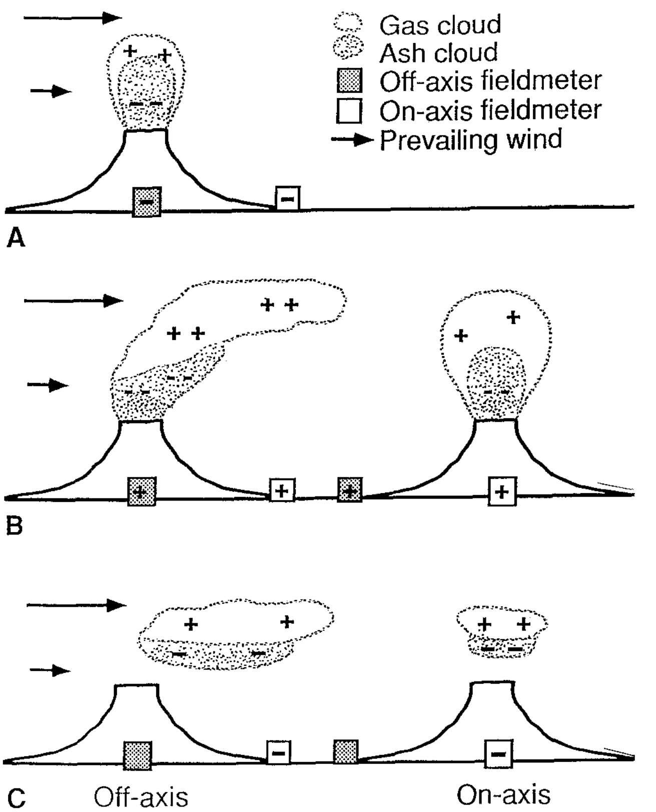

Fig. 4. Schematic representation of the growth and dissipation of an eruption plume to explain changes in potential gradient measured at ground level

fragmentation of magma, do result in the generation of charged solid particles and volcanic gases (ions).

Explosive eruptions resulting in ash generation exhibit sequences of potential gradient reversals (Fig. 1a, b). These reversals may be explained in this case by assigning an average negative charge to ash particles and an average positive charge to the erupted gases (which condense to yield positively charged liquid drops). Figure 4 shows one series of possible explanations for the potential gradient reversals. In the early stages of the eruption (Fig. 4a) positively charged gases separate from the ash at the top of the column due to gravitational forces. Agglomeration of the ash would enhance this process by increasing the terminal fall velocities of fine-grained ash particles at the top of the cloud. Separation causes the initial negative potential gradient pulse seen in both on-axis (Fig. 1a) and off-axis (Fig. 1b) data. This is due to the negatively charged (on average) base of the column being closer to the field meter than the positively charged (on average) top of the column. A laterally spreading gravity current develops (Fig. 4b). Higher wind speeds accelerate the gases ahead of the ash at high altitudes and give rise to the positive potential gradient in the on-axis data (Fig. 1a). Gases escaping from the side of the plume generate a positive potential gradient in the off-axis data (Fig. 1b). In the final stages of the eruption (Fig. 4c) the plume recedes from the off-axis fieldmeter generating the near exponential decay in potential gradient (Fig. 1b). As the plume moves over the on-axis fieldmeter negatively charged ash-laden regions of the plume dominate the potential gradient and the near exponential decay, as the plume retreats, is punctuated by periods of ashfall (Fig. 1a).

Hatakeyama and Uchikawa (1952) proposed a dipole model, but assigned charge of one sign to large ash particles and charge of the other sign to small ash particles. We see no physical justification for particle size to control charge polarity of insulating particles since charge transfer on contact is driven by differences in surface work function, which depends on surface composition. (The surface composition of an ash particle may be substantially different from the bulk particle composition.) Previous workers (Hatakeyama and Uchikawa 1952; Hatakeyama 1958) have suggested that charging of ash particles occurs within the plume due to grain-grain collisions. This mechanism does not adequately explain the generation of charged gaseous species which condense to form charged liquid drops. We propose that charge is generated by fracto-emission (Donaldson et al. 1988) processes during vesiculation and fragmentation of magma within the vent, where ash generation is taking place. This yields both charged volcanic gas (ions) and ash particles. The generation rates of charged material within a convecting low-density plume must be significantly lower than within the fragmentation zone. The polarity of the charges generated may depend on the volcano or eruption studied (Hatakeyama and Uchikawa 1952; Anderson et al. 1965) and may be a function of magma chemistry. We hypothesise that the total amount of charge generated per unit mass of erupted material is a function of particle size (surface area) and that explosions which generate large quantities of fine ash (such as during phreatomagmatic eruptions) create more charge per unit mass than during dry (e.g. plinian style) eruptions.

We have carried out a crude calculation in order to (1) estimate the mass of ash that would require separation (by gravity) from the erupted gases to yield the observed potential gradients, and (2) show that this estimate is consistent with values of ash mass loadings in volcanic plumes. In order to generate a potential gradient of 2.5 $kV\,m^{-1}$ (e.g. Fig. 1a), we calculate that a minimum excess (positive plus negative) charge concentration in the gas cloud of approximately 10^{10} elementary charges per cubic meter ($e\,m^{-3}$) is required if a gas/ash separation distance of 10 m is assumed. This separation distance is based on a terminal fall velocity for ash clusters of 0.35 $m\,s^{-1}$ (Carey and Sigurdsson 1982) and a time scale of ~ 30 s. Similarly, Anderson et al. (1965) calculated an excess (positive plus negative) charge of $2\times10^{10}\,e\,m^{-3}$ for the 1964 eruption cloud of Surtsey. Our calculation, assuming the same excess charge concentration for the ash cloud (i.e. the total erupted material is electrically neutral), a value of surface charge density of $10^{-5}\,C\,m^{-2}$ (Gilbert et al. 1991) and 25 μm diameter particles, gives an excess charged particle concentration of $10^5\,m^{-3}$. This yields an excess mass loading of $10^{-6}\,kg\,m^{-3}$ of charged fine-ash particles that would require separation from the volcanic gases in order to produce the potential gradients recorded. Hatakeyama (1958) found a charge to mass (Q/m) ratio for falling ash of $-4\times10^{-7}\,C\,kg^{-1}$ (i.e. the sum of positive and negative charges on the ash). Gilbert et al. (1991) separated the positive and negative ash particles and found an absolute (i.e. either positive or negative) Q/m ratio for falling ash of -2 to $-5\times10^{-4}\,C\,kg^{-1}$ for the negatively charged ash and $+3$ to $+6\times10^{-4}\,C\,kg^{-1}$ for the positively charged ash. By comparing these data, which are the only available data (from Asama-yama and Sakurajima volcanoes), this implies that the excess charge may be carried by approximately 0.1% of the ash. Therefore, the total mass loading of the Sakurajima plume may be of the order of $10^{-3}\,kg\,m^{-3}$.

Assuming that the material leaves the vent as 2 wt% water vapour and 98 wt% ash the average density is $\sim 50\,kg\,m^{-3}$ on exiting from the vent. It was observed that the eruption column expanded to a diameter of approximately 1.5 km at about 3 km above the vent before spreading laterally at its height of neutral buoyancy in the atmosphere. The vent diameter is estimated to be 15 m. This yields a horizontal cross sectional area ratio of 10^4 as a measure of the plume expansion. Therefore, between the time the first erupted ash exited from the vent and the time it reached its height of neutral buoyancy, the density of the plume decreased (by a factor of approximately 10^4) to $5\times10^{-3}\,kg\,m^{-3}$.

To show that the two estimates for the mass loading within Sakurajima's plume are reasonable it is interesting to note that the Mount St. Helens initial eruption cloud of 18 May 1980 was calculated to support a total of $8.5\times10^{-3}\,kg\,m^{-3}$ of fine ash (Harris et al. 1981). Therefore, only a small imbalance in the concentration of positive and negative charges in the ash and gas clouds is required to produce the observed potential gradient fluctuations.

Acknowledgements. We thank K Kamo and staff of the Sakurajima Volcanological Observatory for valuable assistance during fieldwork. We thank T Koyaguchi for logistical help in the field. SJL thanks the Royal Society for field and apparatus expenses. JSG is grateful to the NERC for a Research Fellowship. RSJ Sparks, CJN Wilson and CPMA Jaupart gave valuable comments.

References

Anderson R, Bjornsson S, Blanchard DC, Gathman S, Hughes J, Jonasson S, Moore CB, Survilas HJ, Vonnegut B (1965) Electricity in volcanic clouds. Science 148:1179–1189

Carey SN, Sigurdsson H (1982) Influence of particle aggregation on deposition of distal tephra from the May 18, 1980, eruption of Mount St. Helens volcano. J Geophys Res 87:7061–7072

Chalmers JA (1967) Atmospheric electricity. Pergamon Press, London, pp 515

Chubb JN (1990) Two new designs of 'field mill' type fieldmeters not requiring earthing of rotating chopper. IEEE Transactions on Industry Applications 26:1178–1181

Crozier WD (1964) The electric field of a New Mexico dust devil. J Geophys Res 69:5427–5429

Donaldson EE, Dickinson JT, Bhattacharya SK (1988) Production and properties of ejecta released by fracture of materials. J Adhesion 25:281–302

Freier GD (1960) The electric field of a large dust devil. J Geophys Res 65:3504

Gilbert JS, Lane SJ, Sparks RSJ, Koyaguchi T (1991) Charge measurements on particle fallout from a volcanic plume. Nature 349:598–600

Harris DM, Rose WI, Roe R, Thompson MR (1981) Radar observations of ash eruptions. US Geol Surv Prof Pap 1250:201–207

Hatakeyama H (1958) On the disturbance of the atmospheric electric field caused by the smoke-cloud of the volcano Asama-yama. Pap Met Geophys Tokyo 8:302–316

Hatakeyama H, Uchikawa K (1952) On the disturbance of the atmospheric potential gradient caused by the eruption-smoke of the volcano Aso. Pap Met Geophys Tokyo 2:85–89

Iribarne JV, Cho H-R (1980) Atmospheric physics. D Reidel Publishing Company, Holland, pp 212

Ishihara KJ (1985) Dynamical analysis of volcanic explosion. J Geodynamics 3:327–349

Ishihara KJ (1990) Pressure sources and induced ground deformation associated with explosive eruptions at an andesitic volcano: Sakurajima volcano, Japan. In: Ryan MP (ed) Magma transport and storage. John Wiley and Sons, Chichester, pp 335–356

Kamo K, Ishihara K (1989) A preliminary experiment on automated judgment of the stages of eruptive activity using tiltmeter records at Sakurajima, Japan. In: Latter JH (ed) Volcanic hazards. Springer-Verlag, Berlin, pp 585–598

Whitlock WS, Chalmers JA (1956) Short period variations in the atmospheric electric potential gradient. Quart J R Met Soc 82:325–326

Editorial responsibility: C. Jaupart