Electrostatic phenomena in volcanic eruptions

S J Lane, M R James and J S Gilbert
Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
s.lane@lancaster.ac.uk

Abstract. Electrostatic phenomena have long been associated with the explosive eruption of volcanoes. Lightning generated in volcanic plumes is a spectacular atmospheric electrical event that requires development of large potential gradients over distances of up to kilometres. This process begins as hydrated liquid rock (magma) ascends towards Earth's surface. Pressure reduction causes water supersaturation in the magma and the development of bubbles of supercritical water, where deeper than c. 1000 m, and water vapour at shallower depths that drives flow expansion. The generation of high strain rates in the expanding bubbly magma can cause it to fracture in a brittle manner, as deformation relaxation timescales are exceeded. The brittle fracture provides the initial charge separation mechanism, known as fractoemission [1]. The resulting mixture of charged silicate particles and ions evolves over time, generating macro-scale potential gradients in the atmosphere and driving processes such as particle aggregation. For the silicate particles, aggregation driven by electrostatic effects is most significant for particles smaller than c. 100 µm. Aggregation acts to change the effective aerodynamic behaviour of silicate particles [2], thus altering the sedimentation rates of particles from volcanic plumes from the atmosphere. The presence of liquid phases also promotes aggregation processes [3] and lightning.

1. Introduction
The presence of electrical phenomena in volcanic eruptions, specifically explosive eruptions, has long been known and is exemplified by lightning [see review by Mather and Harrison, 4]. Electric charge is highly heterogeneous at the scale of atoms and molecules, but to have a macroscopic effect this heterogeneity must increase its scale through a series of physical and chemical processes. In the case of volcanic lightning this scale is of order kilometers, an increase of c. $10^{13}$.

2. Magma fragmentation
Volcanoes are the product of molten rock (magma) emerging at Earth's surface. The molten rock is produced by partial melting at depths of 10s to 100s of km, resulting in a melt phase that, at high pressure, has water and other volatile species dissolved in it. The melt ascends buoyantly in Earth's crust and, when pressure is reduced to the extent that water is supersaturated in the magma, bubbles nucleate and grow. This process causes expansion, reduces density and drives magma to the surface. If the magma is of medium to high viscosity (> c. $10^4$ Pa s) then some form of explosive event involving magma fragmentation [5] by brittle failure is likely.
2.1. Fractoemission

The fracturing of solid materials necessarily involves disruption of the atomic-scale electric fields that bind solids together. If fracture propagation speeds are sufficiently rapid that relaxation of the perturbed electrical structure cannot decay within the solid, then a range of phenomena can occur. These include the emission of photons, electrons and positive ions as well as the creation of charged fragments of the solid; this is the process of fractoemission [1].

The magma fragmentation process occurs at a range of depths below and heights above the Earth’s surface. Initial fragmentation can take place several 100s m below ground level, with the clasts generated continuing to fragment during collisions [6] and continuing gas expansion. The fragmentation process results in clasts generally ranging from metres to less than a micron in size, representing a very large surface area of fresh fracture surface. The collapse of lava domes to produce avalanches of pyroclasts produces similarly high degrees of fragmentation. It is thought that fractoemission begins the process of increasing the scale of charge heterogeneity, and is the dominant pathway for the initial generation of charged particles in particulate volcanic flows.

2.2. Atmospheric interaction

On interaction with the atmosphere the large surface area resulting from the small particle sizes promotes rapid heat exchange with cold entrained air. Should the average density of the hot mixture of rock particles and air be less than that of the surrounding atmosphere, a thermally buoyant volcanic plume develops and can range in height from a few 100 meters to 10s of kilometers, depending on the thermal (mass) flux of the eruption.

The processes involved in plume development can act to further separate the charged plume components. There is field [7] and experimental [8] evidence that gas and/or small particles take an average positive charge, whilst larger particles are negative on average. The origin of this process may lie in the partitioning of charge between ions and silicate fragments during the fragmentation process and from interactions with the atmosphere.

3. Electrostatic aggregation

The products of magma fragmentation are silicate particles, water vapour and other gases such as SO₂ and halogens. The larger sizes of hot silicate particles (pyroclasts) are not coupled to the gas phase and follow ballistic trajectories (Figure 1). The small particles (ash) couple more strongly to the gas phase and are lofted in the buoyant plume. The presence of unbalanced electric charge on the surface of silicate particles < c. 100 µm in size promotes aggregate formation [2] (Figure 2a), with the presence of a liquid phase (Figure 2b) enhancing this process [3]; note that > 50 % by mass of explosive volcanic products are in this size range.

Particle aggregation has a profound effect on sedimentation from volcanic plumes, acting to increase the effective fall velocity of any particle within the aggregate [9]. Hence, small ash particles are more rapidly removed from the atmosphere than if they were transported as individuals. This process is implicated in the development of bimodal particle size distributions and in ash deposits that increase in thickness with distance from the volcanic source.

4. Atmospheric potential gradients

Close to the volcanic source, the charge associated with volcanic ejecta can dominate the electrical environment of the local atmosphere and perturbs the fair-weather atmospheric potential gradient. The potential gradient can be used to imply charge distributions and magnitudes within the volcanic plume [4] and models suggest that one charge tends to dominate the upper reaches of the plume, whereas the lower reaches are dominated by the opposite polarity. The details of how charge separates remains poorly constrained, but possibilities include gas and small particles taking one charge, and large particles another.
The fallout of volcanic ash at measurement localities indicates that larger particles often have a net negative charge, but this polarity may vary between eruptions and volcanoes. Laboratory experiments have shown that the fracture of pumice generally produces ions of a net positive charge and ash particles of a net negative charge [7][8]. It is hypothesized that, over time, the large surface area presented by small particles scavenges more ions, leaving large particles more negatively charged than small particles on average. Gravitational separation then acts to produce the observed atmospheric potential gradients.

5. Volcanic lightning
Volcanic lightning is the result of potential gradients exceeding the electrical breakdown strength of the atmosphere, a process that may also take place on other solar system bodies [10]. McNutt and Williams [11] provide a contemporary review of volcanic lightning. The mechanisms of electrification in plumes 1 - 4 km high may be attributed to fragmentation processes, whereas lightning in plumes 7 - 12 km high may also involve electrification mechanisms seen in thunderclouds. Evidence for the involvement of freezing processes in the generation of lightning detectable by long range meteorological observation comes from the recent Eyjafjallajökull eruption of 2010 [12]. Thus there appear to be at least two mechanisms leading to lightning, namely magmatic mechanisms giving discharges near the vent and at temperatures above c. -20°C, and atmospheric mechanisms associated with water freezing below c. -20°C.

Figure 1. Sakurajima volcano, Japan, with lightning (10th February 2010). The ballistic trajectories represent hot magma clasts, with the electric discharge following an apparently more random path. The close proximity of the electric discharge to the crater rim suggests that the charge separation mechanisms operating are different from those leading to larger-scale meteoric lightning (reproduced with the kind permission of Martin Rietze http://apod.nasa.gov/apod/ap100210.html).

Figure 3. Lightning propagates within the eruption plume of Kirishima volcano, Japan. This suggests that the potential gradient required to cause electrical breakdown in the plume is less than that required for free air. This hypothesis would appear consistent with the presence of many charged particles and ions within the plume. The dominant charging mechanisms here are likely to be sourced in the fragmentation process, specifically fractoemission mechanisms during brittle fracture of magma.

The reader can find many spectacular images of volcanic lightning online. Figure 3 shows lightning occurring during the Kirishima eruption in late January 2011. This image suggests that the lightning is here confined within the plume, implying that the electrical properties of the plume are more conducive to electrical breakdown than the surrounding atmosphere; the plume is acting as a lightning conductor. Large lightning strikes, very similar to those seen from thunderstorms, are also observed.
from large volcanic clouds some distance from the eruption source, and these lightning strikes pose a fatal hazard in their own right.

Volcanic lightning has been identified as a potential fixation mechanism for nitrogen [13], making this element available for biological processes. The fixation rates are estimated at $10^{13}$ g NO per year about 4 Ga ago and are comparable with other nitrogen fixation mechanisms, such as meteoric lightning, hot volcanic vents and bolide impacts, during the early history of Earth and other planets.

![Figure 2a](image1.png)

**Figure 2a.** The presence of liquids promotes the formation of spherical aggregates of volcanic particles known as accretionary lapilli.

![Figure 2b](image2.png)

**Figure 2b.** The absence of liquids creates aggregates with fractal geometries, here imaged in flight. The scale bar is 0.5 mm long.

### 6. Conclusions
Electrostatic phenomena have a significant impact on volcanic plumes by causing a profound change in the sedimentation behaviour of small ash particles. The presence of lightning is spectacular and can give a detectable signal for the remote monitoring of volcanic activity. Changes in atmospheric potential gradient provide data on the magnitude and sign of charge distribution in volcanic plumes, but much research remains to be done into all these phenomena to improve our fundamental understanding and the implications for eruption monitoring.

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