Proc. ESA Annual Meeting on Electrostatics 2015

The Electrification of Volcanic Particles during the Brittle Fragmentation of the Magma Column

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***Abstract* -- Volcanic plumes, turbulent clouds of fine-grained ash, tend to become electrostatically charged. Perhaps the most evident result of this electrification are the impressive electric storms that often accompany vigorous eruptions. While volcanic lightning has been reported for millennia, the physics that generate and separate charge in plumes still require clarification. Proposed mechanisms for electrification include fracto-emission charging or charging resulting from the break-up of magma in the conduit [1], triboelectric charging arising from particle-particle collisions [2], inductive charging of dry materials [3], and charging mechanisms similar to those found in thunderstorms [4]. In this work we delineate a set of experiments designed to elucidate the electrification of particles via fragmentation processes. We show that electrification by fracture is an efficient electrification mechanism. Particles achieve charges close to their saturation values and tend to form agglomerates. These results have important implications for the both the generation of lightning during volcanic eruptions and for estimating the residence time of ash in the atmosphere.**

I. INTRODUCTION

Volcanic plumes, like many other turbulent granular systems in nature, have the tendency to become electrostatically charged. Perhaps the most dramatic and evident consequence of this electrification are the impressive lightning displays often observed during vigorous eruptions. While volcanic lightning has been reported for millennia, the physics that generate and separate charge in plumes still require clarification.

Observations of volcanic lightning storms during the 2006 Augustine eruption [5] and the 2009 Redoubt eruption [6] have revealed two principal discharge modalities: i) Small (1-10 m in length), chaotic discharges localized near the volcanic vent (within the gas-thrust region) and ii) larger, more organized strokes generated within the elevated regions of the plume. The production of plume lightning has been attributed to electrification mechanisms similar to those described in conventional thunderstorms, specifically processes involving the interaction of ash and hydrometeors [4]. Conversely, the physics that generate the observed near-vent lightning remain more elusive. Cimarelli et al., 2014 have reproduced "volcanic lightning" experimentally by accelerating a volume of ash at high pressures using a shock tube, suggesting that volcanic material becomes electrified by triboelectric charging [2], [7]. A second electrification method, often referred to as *fracto-emission* or *fragmentation charging*, deals with the generation of charge during the brittle disruption of magma in the volcanic conduit [8]. Magmatic fragmentation is initiated as a melt rises to toward the surface. As the hydrostatic pressure decreases, volatiles exsolve to form bubbles. For silica-rich magmas, which undergo extensive polymerization, the rate of bubble growth is often too fast for the melt to respond visco-elastically, resulting in the catastrophic breakup of the magma into a granular flow composed of fine, glassy particles suspended in a gas matrix. Fragmentation of the ascending magma column, and the associated charging of particles, occurs several kilometers in depth, precluding any direct observation of these processes [9].

Electromagnetic phenomena associated with fragmentation are not unique to volcanic systems. Similar processes have been described extensively during the opening of cracks in materials such as rock, ice, metal, and polymers [10]. However, a cohesive theory to explain why matter becomes electrified when fragmented has yet to be formulated. For rocks, previous work has pointed to the piezoelectric properties of some minerals (e.g. quartz) which generate potentials when strained [11]. Studies of precursory seismo-electromagnetic phenomena have suggested that charging of deformed rocks is produced by fluids passing (streaming potential) through newly-generated or modified pore networks. Nonetheless, fracture charging has been observed in homogenous substances containing neither piezoelectric materials nor fluids. Takeuchi et al., 2004 have shown that even materials of very high purity tend to become charged, attributing this electrification to the trapping centers inherently contained in most materials [10].

While fragmentation charging is widely quoted in the literature as one of the principal drivers of volcanic lightning (e.g. [1], [4], [6], [7], [12]), little experimental work has been performed on the subject. Perhaps the most important, if not the only, endeavor designed to quantify fracto-emission charging of volcanic material has been that of James et al., 2000 [1]. By disrupting pieces of pumice (either by impacting or by grinding two pumices together), those authors determined that particles could achieve charge-to-mass ratios close to their theoretical maxima. However, these experiments cannot distinguish triboelectric charging and fragmentation charging, two distinct processes that can generate charging in granular materials.

In this work, we attempt to quantify the charging of particles driven solely by fragmentation processes. Unlike the experiments escribed in James et al., 2000, our work produces charged particles via explosive fragmentation. We show that particles acquire charges close to their saturation values and that such charging leads to the formation of aggregates. These results have important implications for the both the generation of lightning during volcanic eruptions and for understanding ash transport and residence in the atmosphere.

Fig 1: Two Prince Rupert's drops under polarized light. Notice the stress patters. Left drop includes a bubble.

II. METHODS

We developed a methodology to assess the electrification of granular material due to fragmentation processes, while minimizing the effects of other electrification mechanisms. To produce charged particles via fragmentation, a set of 30 soda-lime Prince Rupert's drops were disrupted in a controlled environment. Prince Rupert's drops (PRD) are meta-stable, tadpole-shaped structures formed by quenching molten glass in water [13] (see Fig. 1). The residual stress in the glass caused by the difference in cooling rate between the surface of a drop and its interior gives PRDs some particular characteristics. While the drop's head is extremely strong (it can purportedly withstand several repeated hammer blows), the whole structure explodes violently into micron-sized particles if the delicate tail is even slightly damaged. Under linearly polarized light, the stress in the glass manifests itself as colorful fringes (birefringence, see Fig. 1) [14]. Unlike previous experiments, in which disruption of glass (pumice) was produced by a net input of mechanical energy (by abrading or impacting the sample), the fragmentation of a PRD is driven entirely by the release of stored thermal stress. Indeed, the mechanism of PRD disruption is closer to the fragmentation of a melt during an eruption, which is also driven by stored stress in the material (stemming from the exsolution of volatiles and bubble growth) [15].

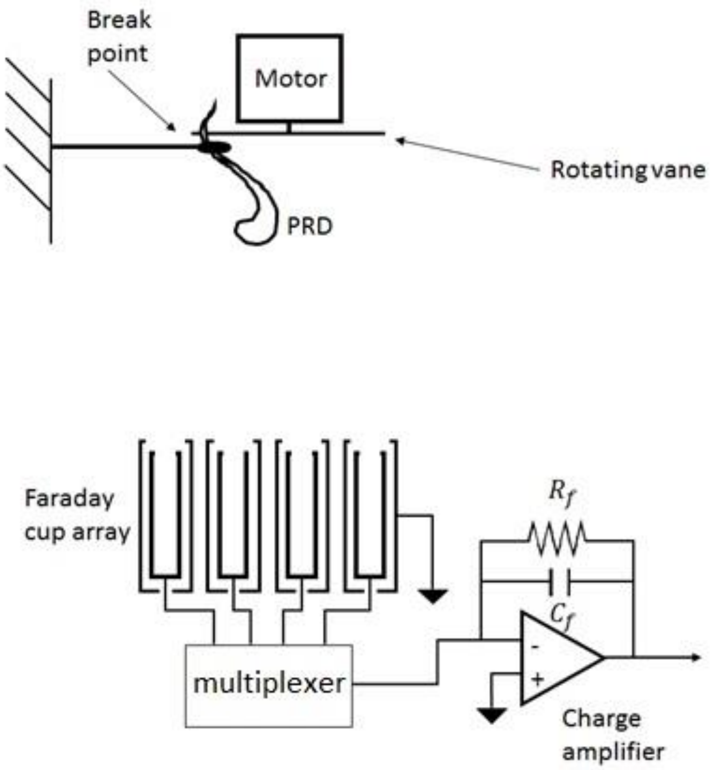

Fig. 2: Schematic of the experimental apparatus. The Prince Rupert's drop is suspended over a set of 4 Faraday cups. An aluminum vane driven by a stepper motor is used to break the drop's delicate tail, causing explosive disintegration. The charge on particles falling into the Faraday cups is measured by a high-resolution charge amplifier.

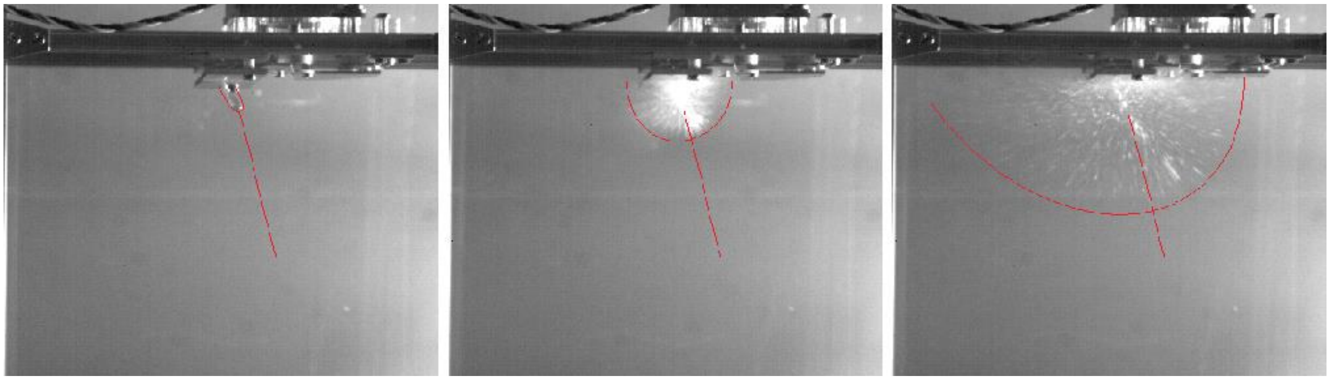

Fig. 3: A sequence of images from a high-speed recording of the disruption of a PRD. Frames are spaced by 2ms. Red curves indicate the explosion front.

The fragmentation apparatus is shown schematically in Fig. 2. At the onset of an experiment, a PRD is suspended by the tail in an aluminum holder positioned ~15 cm above a set of four Faraday cups. A stepper motor is employed to spin an aluminum vane which nicks the tail of the drop. Damage to the tail causes the PRD to shatter explosively. Particles resulting from the fragmentation event are expelled in roughly all directions and a small fraction of these fall into the Faraday cups. The apparatus is housed within an environmental chamber in which we control humidity (25%) and monitor temperature and pressure. A Phantom high-speed camera is used to record fragmentation events at a frame rate of ~2,000 fps.

The four Faraday cups were fabricated from 3/8-in square brass tubing and are mounted directly onto a PCB which also hosts a high-resolution four-channel charge amplifier. We use an amplifier based on the design

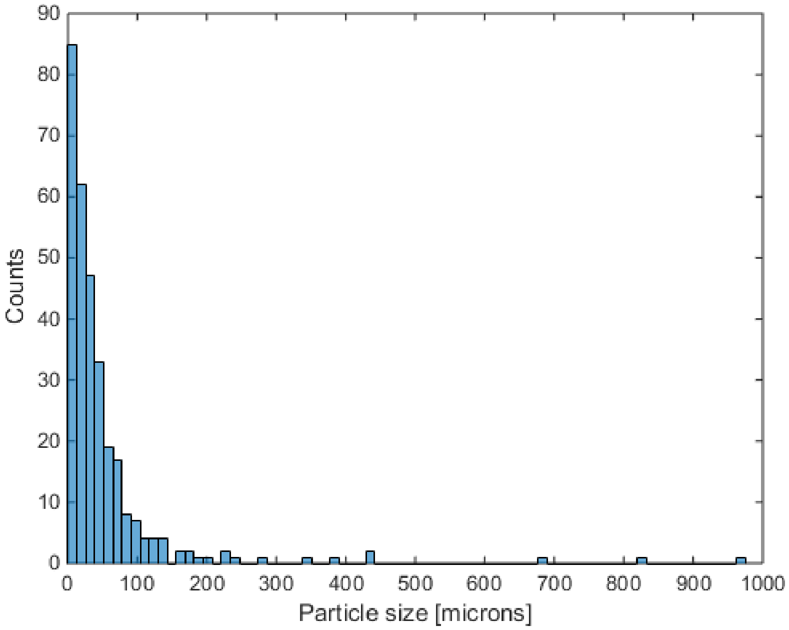

Fig. 4: Size distribution of particles collected from the four Faraday cups at the end of an experiment.

presented in Watanabe et al., 2007 with a resolution of approximately 1 fC/mV [16]. The charge amplifier has a time constant of 0.5 seconds. The output of the amplifier is recorded using a high-speed data acquisition card and a LabVIEW program.

III. PRELIMINARY RESULTS AND DISCUSSION

Fig. 3 displays a select number of frames from a high-speed recording of the explosive disintegration of a Prince Rupert's drop. The first frame shows an unbroken drop. In the second frame, the drop has been ruptured by the rotating vane and the cloud of particles can be seen expanding away radially in the third frame. The time between frames in Fig. 3 is 2 ms. The velocity of the explosion front (indicated in Fig. by the red line) varied between runs, and was estimated to be 13-60 m/s using freely available PIV code (OpenPIV). The size distributions of the particles produced during the fragmentation of a drop were measured by taking photographs of the particles collected in the four Faraday cups and then processing them with Matlab (Fig. 2). Particle diameters ranged from a few microns to several millimeters, with the majority of particles having diameters smaller than 100 microns. The average particle size as determined from the photographic analysis was approximately 80-100 microns. The size distribution of particles is comparable to the size distributions of natural ash described in the literature (e.g. [17], [18]), supporting the idea that the disruption of a PRD has dynamics similar to those in real volcanic fragmentation events. The morphology of some particles from the experiments can be seen in Fig 5. As noted in Cashman et al, 2013, the highly efficient fragmentation process produces particles with features similar to those observed in volcanic ash. Some of these features include "river line" fractures, elongate shapes, platy particles, and fragmented bubble walls [15].

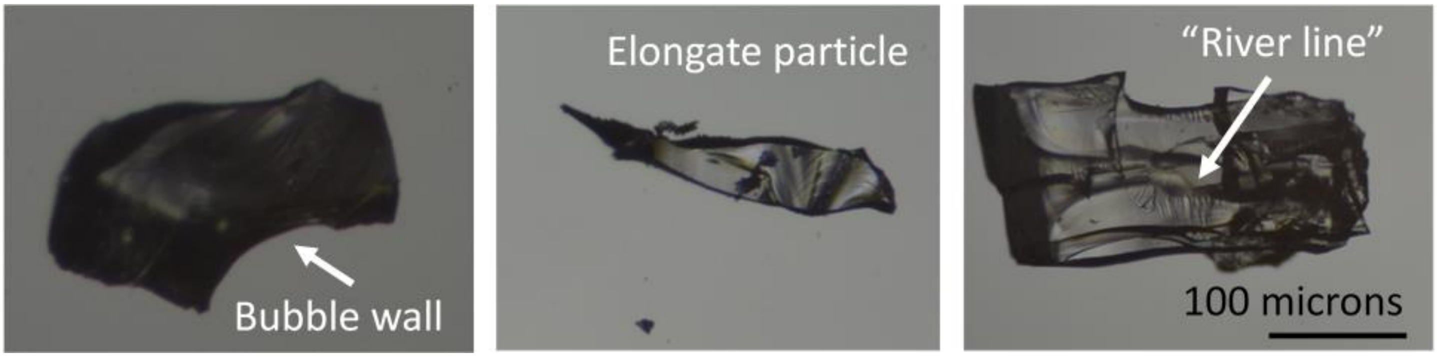

Fig. 5: Particles from a fragmentation event displaying morphological similarities to real ash particles [15].

Fig. 6 shows an example of raw data collected by the DAQ from one Farday cup during a typical run. The abrupt changes in a line's voltage indicate the passage of charged particles into the Faraday cup (arrows in Fig. 6). This voltage then decays back toward zero according to the time constant of the charge amplifier. Particles generated in the fragmentation event charge both positively and negatively, acquiring charges of up to several pico-Coulombs. Fig. 7 show a histogram of the specific charge for a run, computed by dividing the raw charge distribution by the average glass particle mass (assuming a density of $2500\ kg/m^3$).

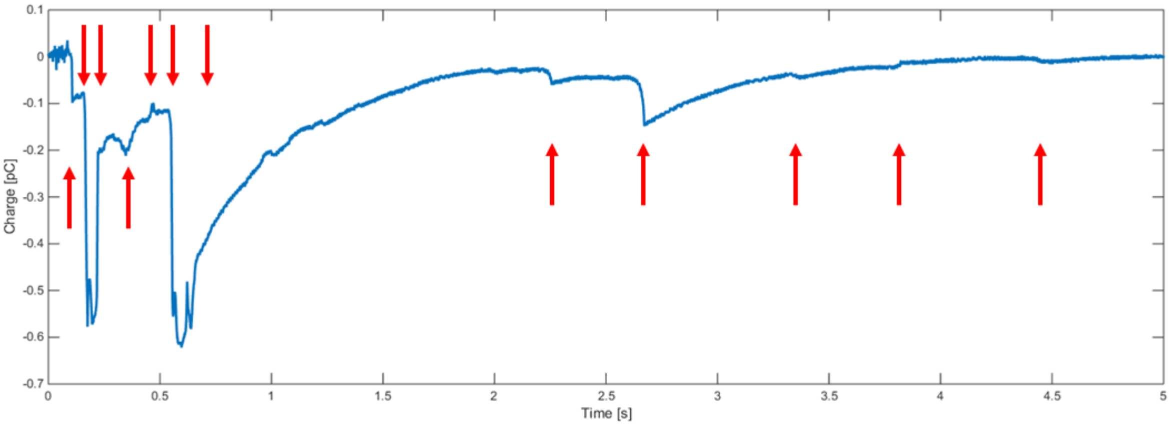

Fig. 6: Raw data as collected from one of the Farday cups during a run. The abrupt changes in line voltage (red arrows) indicate the passage of charged particles into the Farday cup.

For spherical particles, the maximum amount of charge that can be held their surfaces before breakdown of air occurs is given by $Q_{max} = 12\pi\epsilon_o E R^2$ [19]. For particles of several tens to hundreds of microns, as those produced by the disruption of a PRD, the maximum charge that can be sustained is on the order of 10^{-12} to $10^{-11}\ C$. Alternatively, the maximum specific charge expected on such grains would lie between $10^{-4} - 10^{-3}\ C/kg$. While most of the particles acquired *average* specific on the order of $10^{-5} - 10^{-4}\ C/kg$ during a disruption event, charge-to-mass ratios of up to $10^{-3}\ C/kg$ were observed for a few cases (See Fig. 7). The average specific charges obtained in our experiments are comparable to the specific charges detected on particles falling out of plumes. During an eruption of Sakurajima in 1995, for example, Miura et al., 2002 found that particles were both positively and negatively electrified, with specific charges of up to 10^{-5} C/kg [20]. Gilbert et al., 1991 made similar measurement, obtaining charge-to-mass ratios ranging between -5 and 6 $x\ 10^{-4}$ C/kg [21].

The previous experiments investigating fragmentation charging conducted by James et al, 2000 yielded maximum specific charges with magnitudes comparable to those in our experiments [1]. Nonetheless, in that work, a higher proportion of particles were found to have charge-to-mass ratio greater than 10^{-3} C/kg. As mentioned above, those experiments produced charged particles by colliding or grinding two pumice samples together. The reason for these higher particle charges is likely due to the presence of additional charging mechanisms in their experiments (namely conventional frictional and contact electrification). Because both fragmentation and triboelectric processes were involved in that work, the experiments of James et al., 2000 are more representative of the charging that occurs immediately after the main fragmentation event. Once the magma column has been ruptured, pumice pieces undergo further break-up as they transit the length of the volcanic conduit due to clast-clast collisions and collisions with the conduit wall. This *comminution* produces high volumes of ash and reduces the overall size of pumice clasts exiting the vent [9],[22]. We believe that the experiments described in James et al., 2000 reflect the charging associated with post-fragmentation comminution, while our work, in which tribocharging is minimized, is more representative of charging associated with the main fragmentation event itself.

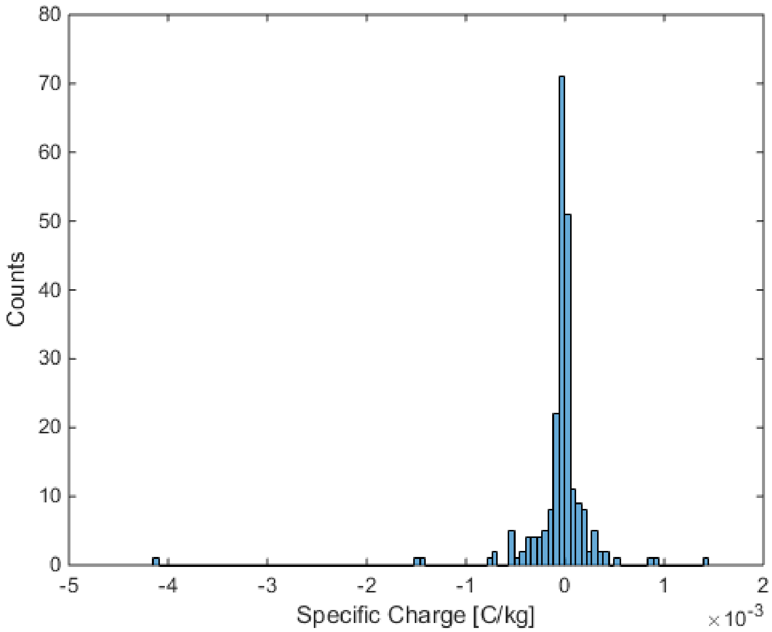

Fig. 7: Histogram of charge-to-mass ratios computed for a typical PRD disruption.

Microscopic analysis of the fragmented samples revealed the presence of aggregates or agglomerates (See Fig. 8). In most cases, aggregates were observed to be composed of a large central particle with a number of smaller particles clustered around it. This arrangement suggests that larger particles hold charges that are opposite in polarity to those held on smaller particles. A similar conclusion was reached by James et al., 2000, who found that aerodynamically-small particles tended to acquire charges of opposite polarity to those on larger fragments. Alternatively, charge may not be distributed uniformly on a particle’s surface, resulting in a patchwork of positive and negative charge which attract small particles of both polarities. Regardless of how charge is arranged, the presence of agglomerates in our experiments indicates that aggregation processes in volcanic plumes become active shortly after the material leaves the vent. Given that aggregates represent effectively larger particles, the formation of these electrostatically-bound structures has important implications for the residence time and transport of ash in the atmosphere [23].

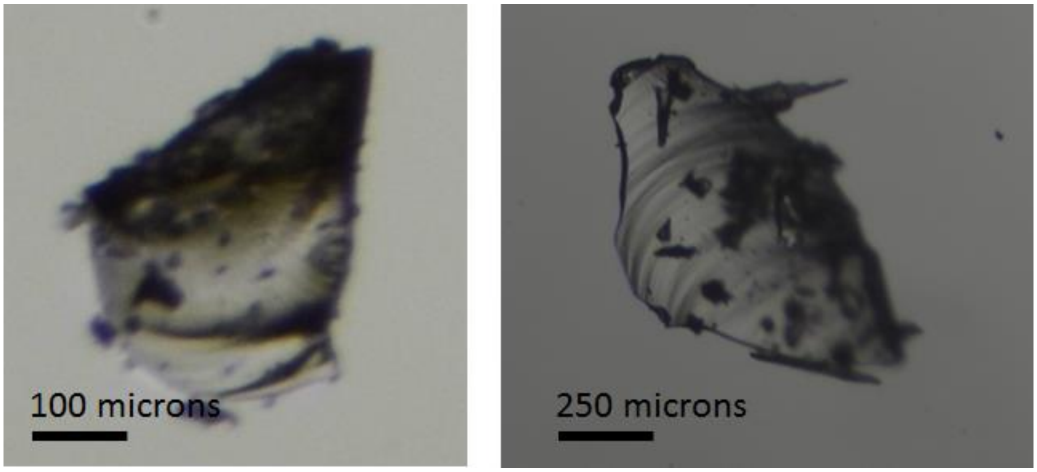

Fig. 8: Photographs showing two aggregates formed by electrostatic forces.

IV. CONCLUSION

In this work, we presented preliminary results on the electrostatic charging of glass particles via fragmentation processes to better understand the electrostatic processes occurring in plumes. We found that particles achieved charge-to-mass ratios similar to those detected during real eruptions. The specific charges in our experiments were slightly smaller than those observed in previous fragmentation experiments. We attribute the difference to the fact that additional charging mechanisms were operating in that work. Finally, the charges acquired by particles during the disruption of PRDs fomented the formation of aggregates.

REFERENCES

[1] James, M. R., S. J. Lane, and Jennie S. Gilbert. "Volcanic plume electrification: experimental investigation of a fracture-charging mechanism." *Journal of Geophysical Research: Solid Earth (1978–2012)* 105.B7 (2000): 16641-16649.

[2] Forward, Keith M., Daniel J. Lacks, and R. Mohan Sankaran. "Methodology for studying particle–particle triboelectrification in granular materials." *Journal of Electrostatics* 67.2 (2009): 178-183.

[3] Pähtz, T., H. J. Herrmann, and T. Shinbrot. "Why do particle clouds generate electric charges?." *Nature Physics* 6.5 (2010): 364-368.

[4] McNutt, Stephen R., and Earle R. Williams. "Volcanic lightning: global observations and constraints on source mechanisms." *Bulletin of Volcanology* 72.10 (2010): 1153-1167.

[5]Thomas, R. J., et al. "Electrical activity during the 2006 Mount St. Augustine volcanic eruptions." *Science* 315.5815 (2007): 1097-1097.

[6] Behnke, Sonja A., et al. "Spectacular lightning revealed in 2009 Mount Redoubt eruption." *Eos, Transactions American Geophysical Union* 93.20 (2012): 193-194.

[7] Cimarelli, Corrado, et al. "Experimental generation of volcanic lightning." *Geology* 42.1 (2014): 79-82.

[8] Lane, S. J., and J. S. Gilbert. "Electric potential gradient changes during explosive activity at Sakurajima volcano, Japan." *Bulletin of volcanology* 54.7 (1992): 590-594.

[9] Dufek, Josef, Michael Manga, and Ameeta Patel. "Granular disruption during explosive volcanic eruptions." *Nature Geoscience* 5.8 (2012): 561-564.

[10] Finkelstein, David, R. D. Hill, and James R. Powell. "The piezoelectric theory of earthquake lightning." *Journal of Geophysical Research* 78.6 (1973): 992-993.

[11] Takeuchi, Akihiro, Hiroyuki Nagahama, and Tetsuo Hashimoto. "Surface electrification of rocks and charge trapping centers." *Physics and Chemistry of the Earth, Parts A/B/C* 29.4 (2004): 359-366.

[12] Mather, T. A., and R. G. Harrison. "Electrification of volcanic plumes." *Surveys in Geophysics* 27.4 (2006): 387-432.

[13] Chandrasekar, S., and M. M. Chaudhri. "The explosive disintegration of Prince Rupert's drops." *Philosophical Magazine B* 70.6 (1994): 1195-1218.

[14] Chaudhri, M. Munawar. "The role of residual stress in a Prince Rupert's drop of soda-lime glass undergoing a self-sustained and stable destruction/fracture wave." *Physica status solidi (a)* 206.7 (2009): 1410-1413.

[15] Cashman, K, E.Nicholson and A. Rust. "Breaking Magma: Controls on magma fragmentation and ash formation." *2nd IUGG-WMO workshop on ash dispersal and civil aviation*, Geneva, 18-20 November, 2013, P-25

[16] Watanabe, Hideo, et al. "New instrument for tribocharge measurement due to single particle impacts." *Review of scientific instruments* 78.2 (2007): 024706.

[17] Aplin, Karen, et al. "Electrical charging of volcanic ash." *Proc. ESA Annual Meeting on Electrostatics*. 2014.

[18] Horwell, Claire J. "Grain-size analysis of volcanic ash for the rapid assessment of respiratory health hazard." *Journal of Environmental Monitoring* 9.10 (2007): 1107-1115.

[19] Horenstein, Mark N., Malay Mazumder, and Robert C. Sumner. "Predicting particle trajectories on an electrodynamic screen–theory and experiment." *Journal of Electrostatics* 71.3 (2013): 185-188.

[20] Miura, Toshiro, Takehiro Koyaguchi, and Yoshikazu Tanaka. "Measurements of electric charge distribution in volcanic plumes at Sakurajima Volcano, Japan." *Bulletin of volcanology* 64.2 (2002): 75-93.

[21] Gilbert, J. S., et al. "Charge measurements on particle fallout from a volcanic plume." *Nature* 349.6310 (1991): 598-600.

[22] Dufek, J., and M. Manga. "In situ production of ash in pyroclastic flows." *Journal of Geophysical Research: Solid Earth (1978–2012)* 113.B9 (2008).

[23] Telling, J., J. Dufek, and A. Shaikh. "Ash aggregation in explosive volcanic eruptions." *Geophysical Research Letters* 40.10 (2013): 2355-2360.