

Lightning-induced volcanic spherules

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ABSTRACT

Glass spherules have been documented in many geologic deposits and are formed during high-temperature processes that include cloud-to-ground lightning strikes, volcanic eruptions of low-viscosity magmas, and meteorite impacts. This study reviews the known glass spherule-forming processes and proposes, for the first time, a mechanism induced through the heat generated by volcanic lightning in eruptive columns and plumes (laterally spreading clouds) during explosive eruptions. Ash-fall samples were collected from two eruptions where volcanic lightning was extensively documented: the A.D. 2009 eruption of Mount Redoubt, Alaska (USA), and the 2010 eruption of Eyjafjallajökull, Iceland. These samples reveal individual glass spherules ~50 μm in average diameter that compose <5% of the examined portion of the deposit. Textures include smooth, hollow, or cracked spherules, as well as aggregates, which suggest melting of ash particles as a result of proximity to the electrical discharge channel and subsequent re-solidification of the particles into spherical morphologies. The natural ash-fall samples are compared with pseudo-ash samples collected from high-voltage insulator experiments in order to test our hypothesis that volcanic ash particles can be transformed into glass spherules through the heat generated by electrical discharge. We refer to this new morphological classification of ash grains as lightning-induced volcanic spherules and hypothesize that this texture not only provides direct physical evidence of lightning occurrence during explosive eruptions, but will also increase settling velocities and reduce aggregation of these particles, affecting ash transport dynamics.

INTRODUCTION

The effects of volcanic ash deposition on electric power systems have been documented following several notable explosive eruptions (see Wardman et al., 2012a), and, of the known impacts, ash-induced insulator flashover (unintended electrical discharge) is the most common. The occurrence of this problem during ash falls created the need for analogue experiments to systematically examine the role of ash properties in inducing flashover across high voltage (HV) insulators (Wardman et al., 2012b, 2014). Ash may also induce volcanic lightning, a common phenomenon during explosive eruptions of various intensities (e.g., volcanic explosivity index [VEI] 2–6; McNutt and Williams, 2010), which data suggest is underreported, perhaps stemming from a perceived lack of evidence in the tephra record. Considering that the melting point of silicate minerals and glasses ranges

from 600 $^{\circ}\text{C}$ to ~1850 $^{\circ}\text{C}$, and that discharges during the flashover process can reach temperatures >3000 $^{\circ}\text{C}$ (Farzaneh and Chisholm, 2009), arcing during flashover may generate temperatures sufficient to melt and fuse ash particles. Studies that have modeled the physical processes of lightning (e.g., Paxton et al., 1986; Rakov, 2013) indicate that temperatures during discharge (30,000 K) are well more than an order of magnitude higher than those required to melt igneous rocks. There is also theoretical (Paxton et al., 1986) and experimental (Cimarelli et al., 2013) evidence for the time scale of this discharge process, which is on the order of several milliseconds, sufficient time for rapid heating of fine (<63 μm) ash particles. Thus, we hypothesize that insulator flashover can be used as a laboratory analogue to volcanic lightning discharge. In the study presented here, we compare textures within the products of

HV flashover experiments to those observed in natural ash-fall samples (from eruptions where volcanic lightning was documented) in order to determine whether volcanic lightning can act as a mechanism for the generation of glass spherules in geologic deposits. We also provide a review of other processes known to create these particular textures under the hypothesis that, in many cases, spherules formed as a result of lightning discharge may be overlooked, despite the evidence they provide of lightning occurrence in eruptive columns and plumes and the effect they have on ash transport and deposition by increasing settling rates while inhibiting particle aggregation.

Table 1 provides a comparison between known glass spherule-forming processes and the lightning-induced volcanic spherules (LIVS) proposed in this study. Glass spherules are found on the surface of Earth as a result of both micrometeorite entry into the atmosphere (e.g., Brownlee et al., 1983; Genge et al., 2008) and larger-scale meteorite impacts (e.g., Glass and Simonson, 2013). Micrometeorites that undergo fusion during atmospheric entry are referred to as cosmic spherules, and the impact of large meteorites on Earth's surface may result in vaporization and melting (as generated temperatures may exceed 10,000 $^{\circ}\text{C}$) of both the projectile and the impacted rocks and/or sediments to form impact spherules (Glass and Simonson, 2013).

Spherical pyroclasts, termed achneliths, may result from eruptions of low-viscosity magmas (Walker and Croasdale, 1971; Carracedo Sánchez et al., 2010). Pele's spheres are achneliths documented in the A.D. 1959 Kilauea Iki deposits (Hawaii, USA). Porritt et al. (2012) performed detailed textural analyses on achneliths formed during the 1959 fire-fountaining episodes and determined that Pele's spheres are capable of forming when the pyroclast is

TABLE 1. GLASS SPHERULES FOUND IN NATURE AND COMPARISON WITH PROPOSED LIGHTNING-INDUCED VOLCANIC SPHERULES

Term	Formation mechanism	Diameter	Characteristics
Pele's sphere	Eruption of low-viscosity magma	<1 mm	Glassy and vesicular with rare surface cracks and protrusions (Porritt et al., 2012)
Cosmic spherule	Melting of micrometeorite during atmospheric entry	<100 μm	Glassy, containing recrystallized and/or relict minerals such as magnetite and olivine (Genge et al., 2008)
Meteorite ablation spherule	Shed from larger meteoroid during atmospheric entry	2 μm –3 mm	Limited compositional range similar to parent body, alkali and metal depleted (Brownlee et al., 1983; Genge et al., 2008)
Microtektite	Meteorite impact	<100 μm –3 mm	Compositional mix of target and projectile materials, microlite-free glass with lechatelierite, <0.02 wt% H_2O (Glass and Simonson, 2013)
Droplet fulgurite	Cloud-to-ground lightning strike	1–2 cm	Si- and Fe-rich glass, vesicles, metal drops (Pasek et al., 2012)
Lightning-induced volcanic spherule	Lightning in eruptive column or plume	<100 μm	Cracked or smooth surfaces, agglomerates, Si rich with lesser Fe, Al, and K, partial vesicle walls

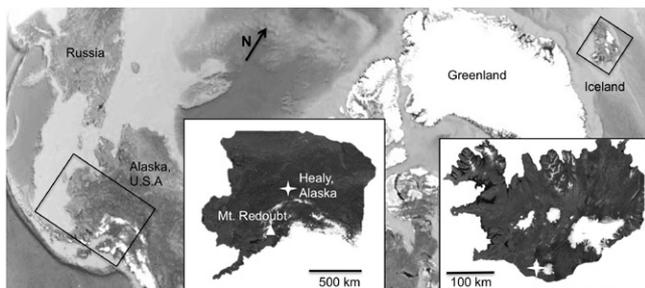


Figure 1. Sample collection locations, with insets showing distal sample location marked by a star in Healy, Alaska, and Mount Redoubt marked by a triangle. In Iceland, the sample was collected proximally to the volcano, Eyjafjallajökull, with both indicated by a star (Google Earth).

of a small enough diameter (<1 mm) to permit relaxation of the outer surface while inhibiting continued expansion of internal vesicles during flight. In addition to those formed during terrestrial volcanic eruptions, glass spherules were documented in lunar samples obtained during the NASA Apollo 11, 15, and 17 missions (McGetchin and Head, 1973; Heiken et al., 1974; Heiken and McKay, 1978; Heiken and Wohletz, 1985).

First documented by Arago (1821), fulgurites are produced when the heat generated by a cloud-to-ground lightning strike melts rocks or sediment, producing glassy, branching cylinders and/or cones that may extend into the substrate for several meters. Droplet fulgurites are on the order of 1–2 cm in diameter, and although rare, are interpreted to form as a result of melt expulsion from the primary fulgurite cylinder followed by subsequent droplet deposition and cooling (Pasek et al., 2012). The existence of fulgurites provides direct evidence that geologic materials can be morphologically altered due to the heat generated by lightning discharge.

METHODS

Ash-fall samples were collected at various distances from the vent following two eruptions where volcanic lightning was documented: (1) the 23 March 2009 eruption of Mount Redoubt, Alaska, USA; and (2) the April–May 2010 eruption of Eyjafjallajökull, Iceland (Fig. 1). Details on sample collection can be found in the GSA Data Repository¹. Lightning was extensively documented during the explosive phase of the Mount Redoubt eruption using the lightning-mapping array (Rison et al., 1999; Thomas et al., 2004; Behnke et al., 2013) and throughout the explosive phase of the 2010 Eyjafjallajökull eruption by the UK Met Office (www.metoffice.gov.uk) long-range lightning location network (Bennett et al., 2010; Arason et al., 2011). Two pseudo-ash samples that replicated the chemical, physical, and electrical properties of freshly fallen ash were bulk manufactured using the procedure developed by Wardman et al. (2012b) for the flashover experiments (details are pro-

vided in Fig. DR1 in the Data Repository). Both natural and post-experimental pseudo-ash samples were examined using the Hitachi, Ltd., TM-1000 scanning electron microscope (SEM) and the XL30 SEM using a working distance of 4–10 mm and 10 mm, respectively. Textures within the ash samples were documented at magnifications ranging from 500× to 3000×, and energy dispersive spectroscopic (EDS) analyses were also performed. Due to the low abundance of these spherules and potential destruction of the samples, no electron microprobe mounts were created. Thus, results presented here are an assessment of size, texture, and general chemistry, with further geochemical analyses a fruitful area of future research.

RESULTS

Spherules were observed in samples from Mount Redoubt (Figs. 2A and 2B) and Eyjafjallajökull (Fig. 2C), but the percentage of spherules is low (<5%) in the distal Mount Redoubt deposits, and only two spherules were observed in the proximal Eyjafjallajökull samples. The natural ash samples contained individual spherules, some of which were cracked or hollow (Fig. 2A), and the Mount Redoubt samples also contained aggregates of numerous spherules, some of which preserved the remnants of vesicle walls (Fig. 2B). Aggregates were not observed in the Eyjafjallajökull samples. Individual spherule sizes range from 9 to 81 μm (average of 48 μm) in diameter for all eruptions (Table 2), while aggregates were composed of individual spherules each ranging from 1 μm to 30 μm in diameter. In some cases, the individual spherules appeared smooth (see Fig. 2C), while in other instances the surfaces were interrupted by holes or cracks that appeared to result from outward expansion of the spherule interior (Fig. 2A). EDS analyses indicate that the spherules are dominated by Si with lower amounts of Al, K, Ca, and Fe.

Spherules were also observed in the pseudo-ash samples collected following HV experiments (Fig. 3). A total of 17 individual spherules were measured, and range in size from 3 μm to 43 μm in diameter, with an overall average diameter of 17 μm (Table 2). All of these spherules appeared to be fused to larger particles (e.g., >500 μm), and in some cases, one side of the spherule is flattened due to welding while

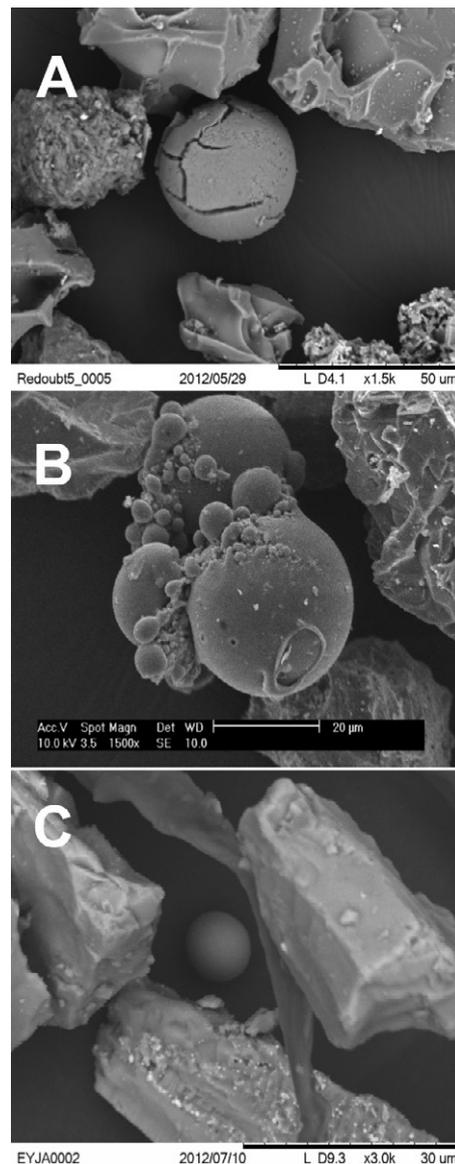


Figure 2. Secondary electron images of lightning-induced volcanic spherules observed in samples from the A.D. 2009 eruption of Mount Redoubt, Alaska, USA (A–B) and the A.D. 2010 eruption of Eyjafjallajökull, Iceland (C). Textures range from almost perfect spheres to spherules displaying surface cracks and holes to aggregates of numerous spherules fused together.

still in a malleable state. The larger particles (Fig. 3A) displayed evidence of partial melting in their shape (fluidal, rounded morphologies), but were not spherical like the smaller particles (Figs. 3B–3D). No aggregates or cracked and/or hollow spherules were observed in the HV experimental products.

DISCUSSION

Sizes of individual spherules are similar (<100 μm) between the natural ash and pseudo-ash samples, but those within the pseudo-ash are generally smaller (an average of 48 μm versus 17 μm, respectively). Some of the spherules in the

¹GSA Data Repository item 2015117, Figures DR1 and DR2, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 2. MEASUREMENTS OF SPHERULES FROM TEPHRA SAMPLES AND FLASHOVER EXPERIMENTS

Sample	Collection location	Material type	Spherule number	Diameter (μm)
Mount Redoubt	63.8731°N 148.0148°W	Natural ash	1	26.0 (1.2)
		Natural ash	2	79.9 (2.9)
		Natural ash	3	80.7 (2.5)
		Natural ash	4	21.2 (0.9)
		Natural ash	5	42.4 (1.6)
		Natural ash	6	40.0 (1.4)
		Natural ash	7	78.5 (5.0)
Eyjafjallajökull	63.5879°N 19.6674°W	Natural ash	1	50.3 (2.1)
		Natural ash	2	9.5 (0.5)
		Natural ash		47.6 (26.9)
Pseudo-ash	43.5235°S 172.5839°W	Pseudo-ash	1	18.4 (0.4)
		Pseudo-ash	2	17.7 (0.4)
		Pseudo-ash	3	11.5 (1.1)
		Pseudo-ash	4	15.1 (0.9)
		Pseudo-ash	5	9.7 (0.2)
		Pseudo-ash	6	25.3 (0.6)
		Pseudo-ash	7	26.0 (0.6)
		Pseudo-ash	8	14.3 (0.8)
		Pseudo-ash	9	17.2 (0.5)
		Pseudo-ash	10	17.7 (0.9)
		Pseudo-ash	11	3.9 (0.2)
		Pseudo-ash	12	5.4 (0.4)
		Pseudo-ash	13	14.7 (0.2)
		Pseudo-ash	14	5.2 (0.0)
		Pseudo-ash	15	51.8 (0.9)
		Pseudo-ash	16	3.0 (0.2)
		Pseudo-ash	17	43.2*
				16.8 (13.3)

*Only one measurement was obtained because the spherule was partially obscured by another particle. All other values are an average of five measurements, with numbers in parentheses indicating the standard deviation. Bold values are an average of all measurements. Error within individual measurements is 0.5 μm .

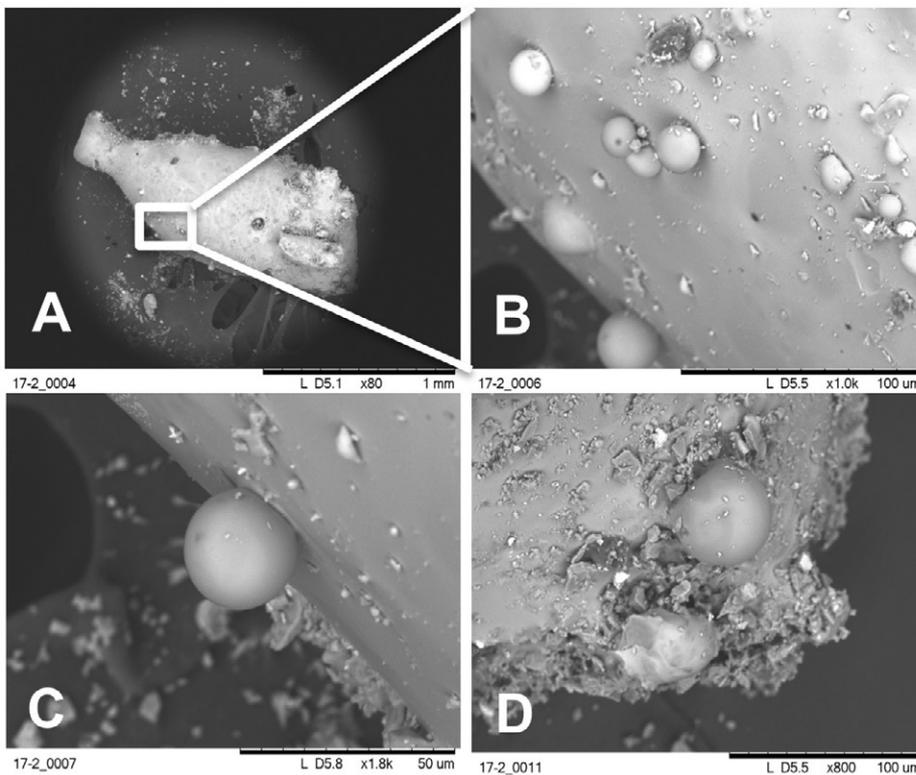


Figure 3. Scanning electron microscope images of pseudo-ash samples collected from tracks of electrical discharge on insulators used in high-voltage flashover experiments. Larger particles (A) display fluidal morphologies indicative of partial melting, but are coated with smaller particles (B–D) with spherical morphologies similar to those found in natural ash-fall samples.

natural ash are hollow or display surface cracks due to apparent expansion of the spherule interior. The hollow, cylindrical morphology of fulgurites formed from cloud-to-ground lightning strikes is hypothesized to result from the flash boiling and expansion of volatiles in the source material, as the electricity will naturally follow paths of increased conductivity (i.e., water) in the geologic units (Pasek et al., 2012). Volcanic ash grains contain structurally bound water and are coated by adsorbed volatiles (e.g., Delmelle et al., 2007) during eruption. Adsorbed volatiles would be vaporized, but expansion of structurally bound volatile compounds during electrical discharge may explain the hollow and/or cracked morphology of volcanic spherules, as observed in Pele's tears (Porritt et al., 2012). Although textures are similar, the magma compositions of Mount Redoubt and Eyjafjallajökull are too viscous (andesite and benmoreite, respectively) compared to that of the Kilauea Iki magma (basalt) to permit the formation of spherical achneliths during primary fragmentation.

The formation of the proposed LIVS appears to be a function of original ash grain size, as all of the observed spherules are $<100 \mu\text{m}$ in diameter despite differences in initial bulk grain-size distribution (GSD; Fig. DR2). Additionally, the pseudo-ash samples reveal that smaller grains were formed into spherules, but larger grains were unable to achieve a spherical morphology (Fig. 3A). The higher number of spherules in the distal Mount Redoubt samples (compared to proximal Eyjafjallajökull samples) indicates that finer-grained, distal deposits will make discovery of these textures easier, and that the spherules (if present) will generally be smaller than the unaltered portion of the tephra, as spheres will settle at a higher velocity, due to decreased drag, than platy ash of the same diameter.

We suggest that spherule aggregates may form from two possible mechanisms. First, we consider the melting of volcanic ash aggregates in the atmosphere. Aggregates represent a ubiquitous component of the 2009 Mount Redoubt tephra and were found in all sampling locations regardless of distance from the vent (Wallace et al., 2013). Distal deposits contained ash clusters (Brown et al., 2012) consisting of irregular groupings of fine ash that disaggregated upon deposition (Wallace et al., 2013), suggesting formation as a result of electrostatic attraction. In general, dry aggregates typically display a maximum diameter of $700 \mu\text{m}$, are composed of individual particles with diameters of $<70 \mu\text{m}$, and, due to their tendency to break apart upon deposition, have a much lower preservation potential compared to wet aggregates (Brown et al., 2012; James et al., 2002, 2003). Here, the bonding of the individual "grains," now fused together, inhibits breakup upon deposition, preserving the overall geometry of the original spherule aggregate. The second possibility is

that individual ash grains are melted due to proximity to the lightning discharge channel and are subsequently fused together in a high-temperature state during atmospheric transport to form the observed spherule aggregates. Observations of spherules formed in the flashover experiments supports this latter mechanism, as some spherules reveal a flattened side where they are bound to larger particles (Figs. 3B and 3D). This implies that smaller grains were melted during electrical discharge and fused to larger particles while still malleable, similar to the formation of droplet fulgurites (Pasek et al., 2012).

CONCLUSIONS

Existence of glass spherules in laboratory-produced ash samples exposed to flashover confirms that the heat generated by electrical discharge can produce these textures, indicating that spherules may form at any location in the eruptive column or plume where volcanic lightning occurs. Despite variations in natural and/or pseudo-ash compositions and initial GSD, all spherules are <100 μm in diameter, suggesting that fine ash is more susceptible to formation of these textures, regardless of composition. Observations suggest that discovery of these spherules will be easier in distal fall samples, although they may be present at all sampling locations. Transformation of irregularly shaped ash particles into spheres will increase the settling rate and reduce the surface area, inhibiting particle aggregation. Observation of LIVS in tephra will provide evidence of lightning occurrence during eruptions where lightning was not directly observed or documented, adding to the growing data set concerning this common, yet significant, volcanic-atmospheric phenomenon.

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