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# Physical properties of volcanic lightning: Constraints from magnetotelluric and video observations at Sakurajima volcano, Japan

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## ABSTRACT

The lightning generated by explosive volcanic eruptions is of interest not only as a promising technique for monitoring volcanic activity, but also for its broader implications and possible role in the origin of life on Earth, and its impact on the atmosphere and biosphere of the planet. However, at present the genetic mechanisms and physical properties of volcanic lightning remain poorly understood, as compared to our understanding of thundercloud lightning. Here, we present joint magnetotelluric (MT) data and video imagery that were used to investigate the physical properties of electrical discharges generated during explosive activity at Sakurajima volcano, Japan, and we compare these data with the characteristics of thundercloud lightning. Using two weeks of high-sensitivity, high-sample-rate MT data recorded in 2013, we detected weak electromagnetic signals radiated by volcanic lightning close to the crater. By carefully inspecting all MT waveforms that synchronized with visible flashes, and comparing with high-speed (3000 frame/s) and normal-speed (30 frame/s) videos, we identified two types of discharges. The first type consists of impulses (Type A) and is interpreted as cloud-to-ground (CG) lightning. The second type is characterized by weak electromagnetic variations with multiple peaks (Type B), and is interpreted as intra-cloud (IC) lightning. In addition, we observed a hybrid MT event wherein a continuous weak current accompanied Type A discharge. The observed features of volcanic lightning are similar to thunderstorm lightning, and the physical characteristics show that volcanic lightning can be treated as a miniature version of thunderstorm lightning in many respects. The overall duration, length, inter-stroke interval, peak current, and charge transfer all exhibit values 1–2 orders of magnitude smaller than those of thunderstorm lightning, thus suggesting a scaling relation between volcanic and thunderstorm lightning parameters that is independent of the type of charged particles. On the other hand, the polarities, which are estimated by long-time (3.4 yrs) MT (32 samples/s) and video (30 frame/s) observations, are different than those of normal thunderstorm lightning. These observations are consistent with the notion that charge structures in volcanic ash plumes are highly disordered and are characterized by numerous small charged regions with high charge density.

## 1. Introduction

Explosive volcanic eruptions frequently generate lightning within and around the eruptive plume. Volcanic lightning is a consequence of plume electrification. Possible mechanisms for plume electrification include fractoemission, particle–particle collisions, boiling of water and the presence of ice and ice-coated particles in the eruptive column (e.g., Buttner et al., 2000; James et al., 2000; Mather and Harrison, 2006; Thomas et al., 2007; James et al., 2008), all of which may result in volcanic lightning by the separation of electrically charged particles. Since a scientific report on the 1963 eruption of Surtsey volcano, Iceland (Anderson et al., 1965), volcanic lightning has been documented intermittently (Brook et al., 1974; Mather and Harrison, 2006; James et al., 2008; McNutt and Williams, 2010). Volcanic lightning

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has been used to monitor volcanic plumes even under adverse weather conditions (McNutt and Davis, 2000; Behnke and McNutt, 2014), and also to investigate inner plume dynamics (Behnke and Bruning, 2015). Particle electrification and discharge (lightning) influence the aggregation of ash particles and ash transport dynamics (Carey and Sigurdsson, 1982; Mather and Harrison, 2006; James et al., 2008). Furthermore, volcanic lightning may impact the Earth's environment (and that of other planets) by fixing nitrogen in a variety of chemical forms, as NO, $NO_2$, $HNO_3$, and $NH_3$ (Mather et al., 2004a). Such $NO_x$ species have a significant impact on ozone concentrations in the atmosphere, and on the fundamental conditions required for the origin and early evolution of life on Earth (Navarro-Gonzalez et al., 1998). However, advancements in our understanding of volcanic lightning, and their impact on the atmosphere and biosphere, have been hampered by our limited understanding of the genetic mechanisms and physical parameters of volcanic lightning.

To understand the physical mechanism of volcanic lightning, one useful approach is to compare and contrast with thunderstorm lightning, which has been studied in increasing detail for decades (e.g., Rakov and Uman, 2003). Based on studies of thunderstorm lightning, particularly the well-studied cloud-to-ground (CG) type, the physical cycle of a lightning discharge can be summarized as follows: (1) collisions of hydrometeors result in electrification; (2) the electric field intensifies due to particle (and hence charge) separation; (3) dielectric breakdown of air results in the development of a conducting channel of ionized gas (a column of charge), called a stepped leader, which propagates in a stepped manner; and (4) rapid transfer of electric charge, the so-called return stroke, which is accompanied by bright optical flashes. Processes (3) and (4) can occur more than once in a single lightning event. In the case of a partially conducting condition of the return stroke channel, a dart leader can be generated, which propagates more rapidly than the stepped leader. A return stroke is often followed by a relatively weak continuing current that persists for tens to hundreds of milliseconds. To date, there has been a lack of observational evidence enabling comparisons of the processes of volcanic and thundercloud lightning.

In the past 10 yrs, modern lightning detection techniques, based on electromagnetic (EM) field radiation in the very high frequency (VHF) range (30 MHz–0.3 GHz), have been used to study Augustine, Redoubt, and Eyjafjallajökull volcanoes (Thomas et al., 2007; Behnke et al., 2013, 2014). Using a VHF array network and the time-of-arrival technique, VHF sources can be located with high precision. Because VHF radiation is generated by dielectric breakdown (e.g., Rakov and Uman, 2003; Behnke and McNutt, 2014), the development of the lightning channel is estimated from the spatio-temporal evolution of VHF sources. Due to its high sensitivity, even a single VHF station is useful in detecting the occurrence of lightning; thus, VHF measurement is a powerful technique in studies of volcanic lightning in particular. However, VHF radiation significantly weakens when the source is not within line-of-sight of the observation point, and VHF sources are essentially not radiated when very strong current flows are associated with process (4). Therefore, in order to capture the complete lightning cycle, it is also necessary to observe the electromagnetic (EM) field at lower frequencies.

Array networks capable of observing radio pulses in the very low frequency range (VLF: 3–30 kHz) have been widely used to monitor thunderstorm lightning. Because VLF signals travel long distances in the waveguide formed between Earth's surface and the ionosphere, these systems cover wide areas and can occasionally be used to detect electrical activity associated with volcanic eruptions. For example, ATDnet, which operates in the UK in a narrow frequency band (~10–14 kHz), detected volcanic lightning during the 2010 Eyjafjallajökull eruption in Iceland (Bennett et al., 2010; Arason et al., 2011). Compared with VHF observations, VLF observations have the advantage of detecting return strokes associated with CG lightning. However, the station coverage in a VLF network is typically too sparse for long-range detection. Weak EM radiation events, originating close to the active vent, are therefore rarely detected (Bennett et al., 2010). Furthermore, when the source and observation sites are several hundreds of kilometers apart, VLF waveforms are strongly influenced by the properties of the propagation path (e.g., Rakov and Uman, 2003). Although a VLF lightning detection network is useful for detecting large eruptions, a custom-designed observation system is needed to study all of the physical processes involved in volcanic lightning. Such regional VLF networks have been deployed to study thunderstorm lightning in Florida, USA (Shao et al., 2006), Alabama, USA (Bitzer et al., 2013), and Europe (Betz et al., 2009), but such a network has not been previously deployed around an active volcano.

Magnetotellurics (MT) is a method commonly used to image subsurface electrical resistivity structure (e.g., Simpson and Bahr, 2005) and its temporal changes (e.g., Aizawa et al., 2011). The MT method, which usually measures two horizontal electric field components and three magnetic field components at the Earth's surface, has recently been used to study volcanic lightning at Sakurajima volcano, Japan (Aizawa et al., 2010). Although the time resolution depends on the sampling rate, MT covers broad-band EM signals with a high dynamic range (24 bit A/D conversion), and therefore can detect weak signals whose amplitudes are smaller than military VLF noise. As compared with conventional antennas used in thunderstorm lightning research, the unique and valuable aspect of MT is that it reproduces true waveforms in real physical units; this is because the frequency characteristics of the sensors and the data logger are all accurately determined in the laboratory. With the MT method, it is possible to determine the timing and polarity of lightning by measuring electromagnetic field variations caused by volcanic lightning, even at distances of several kilometers. However, due to the low sampling rate (as low as 15 samples per second (sps)), the previous study (Aizawa et al., 2010) could not investigate the physical properties of the volcanic lightning cycle; e.g., waveform, electric current, and duration.

In this study, we present new MT data recorded at higher sampling rates (32 sps and 65,536 sps), which are visually correlated with normal and high-speed video observations (at 30 and 3000 frames per second (fps), respectively) in order to study the properties of vent discharges and near-vent lightning (Thomas et al., 2012; Behnke et al., 2013) at Sakurajima volcano, Japan. The high-speed (HS) camera is a powerful tool for investigating the spatio-temporal characteristics of lightning development, and it has recently been applied to thunderstorm lightning research (e.g., Mazur et al., 1995; Ballarotti et al., 2005). Recent HS video observations of volcanic lightning at Sakurajima volcano (Cimarelli et al., in press) confirm the presence of stepped leaders and return strokes. However, the time scale of return strokes, return stroke multiplicity, the existence of continuing current, and the electromagnetic parameters that characterize volcanic lightning have yet to be investigated. Here, we provide observational evidence that allows a comparison of the processes of volcanic and thunderstorm lightning, and we derive estimates of the physical properties of volcanic lightning, especially electromagnetic field variations. In addition, we report on the polarities of volcanic lightning and the inclinations of lightning paths relative to wind directions, examined over a period of 3.4 yrs, using both MT (32 sps) and video (30 fps) observations.

## 2. Observations

Sakurajima volcano is one of the most active volcanoes in Japan. After June 2006, volcanic activity shifted from Minami-dake crater