桜島 MT 連続観測データに含まれる火山雷起源の電磁シグナル

Magnetotelluric Pulses Generated by Volcanic Lightning at Sakurajima Volcano, Japan

相澤広記（東大・地震研），　横尾亮彦（東北大），神田径，小川康雄（東工大）
Koki Aizawa, Akihiko Yokoo, Wataru Kanda, Yasuo Ogawa

Abstract

Continuous magnetotelluric (MT) measurements were conducted at Sakurajima volcano, Japan, revealing syn-eruption electric pulses (and sometimes accompanying geomagnetic pulses). Movies of the eruptions, recorded with timing provided by a GPS clock, show a large number of volcanic lightning flashes. Some MT pulses occurred simultaneously with lightning flashes. Pulses were only observed after more than 10 seconds had passed after the onset of eruption, and were more common during large "effusive" eruptions rather than during small-scale "explosive" Vulcanian eruptions. The observations suggest that the dominant mechanism of volcanic lighting is similar to that of lightning in thunderstorms, in that it requires the collision of particles and subsequent separation of positive and negative charge.

1. Introduction

Volcanic eruptions may generate lightning within and around ash plumes. A recent increase in the availability of spectacular images and movies of volcanic lightning has captured the interest not only of scientists but also of the general public worldwide. However, its formation mechanism remains poorly understood in several regards. For example, the suggested location and timing of particle electrification remains debated [Anderson et al., 1965; Brook et al., 1976; Hoblitt, 1994; McNutt and Davis, 2000; Thomas et al., 2006]. Moreover, the microscopic electrification mechanism remains a topic of controversy [e.g., Lacks and Levandovsky, 2007; James et al., 2008; Pähtz et al., 2010]. The paucity of direct observations of volcanic lightning represents a limitation in terms of understanding its origin.

One useful approach in this regard is to characterize the features of volcanic lightning based on long-term observations. In this study, we analyze lightning at Sakurajima volcano, Japan, recorded by ground-based observations. The features of the electromagnetic signal are investigated with the aim of determining the mechanism of lightning formation.

2. Observations

Continuous magnetotelluric (MT) observations were carried out at Sakurajima volcano in southern Kyushu, Japan. Sakurajima is an andesite–dacitic volcano characterized by Vulcanian eruptions (~8000 explosions in the past 50 years), effusive eruptions, and continuous ash emissions. Since 1955, eruptions have occurred at the summit crater (Minami-dake); however, Showa crater, located 500 m east of Minami-dake, started to erupt in June 2006 after lying dormant for 58 years [Yokoo, 2009].

In 2008, we established two MT sites at Sakurajima (Fig. 1) with the aim of detecting temporal changes in subsurface electric resistivity related to volcanic activity [Aizawa et al., submitted manuscript]. Naturally occurring geomagnetic fields and earth electric currents were measured using Phoenix MTU5 systems with a GPS clock. Geomagnetic fields were measured by induction coils, and electric currents (voltage difference) were measured by wires to which electrodes were attached_at each end. In this study, we analyze continuous 15 Hz data from which high-frequency variations have been removed using an anti-aliasing filter. At a site located 100 m from KURMT observation site, a GPS-clock-synchronized movie was continuously recorded by video tape recorder (VTR) [Yokoo et al., 2009].

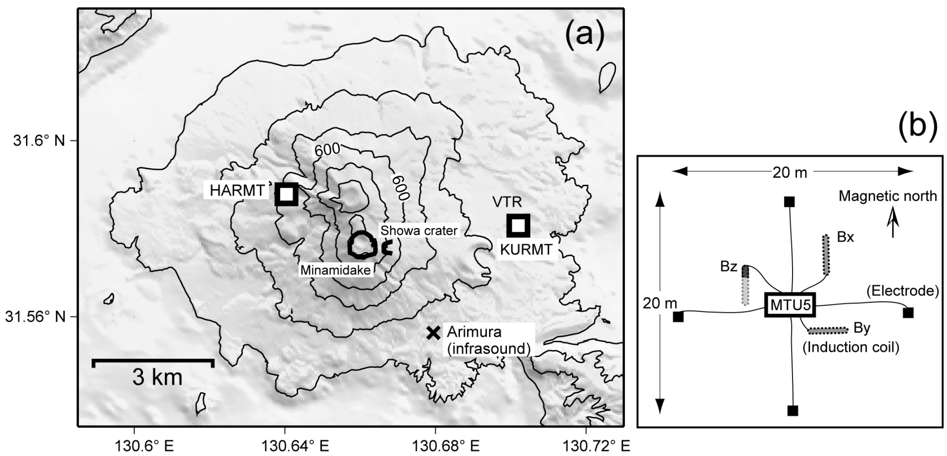

Fig. 1. (a) Topographic map showing the locations of MT sites at Sakurajima volcano (squares). (b) Layout of the MT measurement system. A Phoenix MTU5 system was used to measure variations in the electric (Ex and Ey) and geomagnetic field (Bx, By, and Bz), where magnetic north (x), magnetic east (y), and downward (z) are assigned positive values.

3. MT Pulses

We analyzed 94 eruptions at Showa crater from May 2008 to July 2009, during which time both MT data and movies were recorded. We applied a Fourier transform to the raw 24-bit MT time series, and incorporated the frequency response of the MTU5 system. Next, the time series (in physical units of mV/m and nT) were obtained by an inverse Fourier transform. DC and low-frequency variations were then removed by applying a moving average with a 2 sec time window.

Figure 2 shows an example of the MT data and snapshots of a movie of an eruption. In the case of nighttime eruptions, lightning flashes are observed, synchronous with a pulse (hereafter termed an MT pulse) in the MT record (Fig. 2d), indicating the MT pulse is generated by the lightning. A close examination of the pulses reveals that they occur at one or two sampling points in the 15 Hz time series. The vertical magnetic field (Bz) is insensitive to the lightning.

We evaluated the origin time, amplitude, and arrival directions of pulses. In this study, an MT pulse is defined in the case that the amplitude of Ex or Ey exceeds 0.002 (mV/m). Because MT data collected at KURMT are of relatively low quality, we only used HARMT data in defining the origin time of each pulse. According to the above criteria, pulses were identified in 36 of 94 eruptions, amounting to a total of 105 pulses.

Figure 3 shows a rose diagram of the arrival directions of MT pulses derived from the amplitude ratios (Ex/Ey and Bx/By). Long axes in each diagram reveal that electric current flows approximately along the direction of the crater, whereas the geomagnetic field is mainly oriented perpendicular to the electric current.

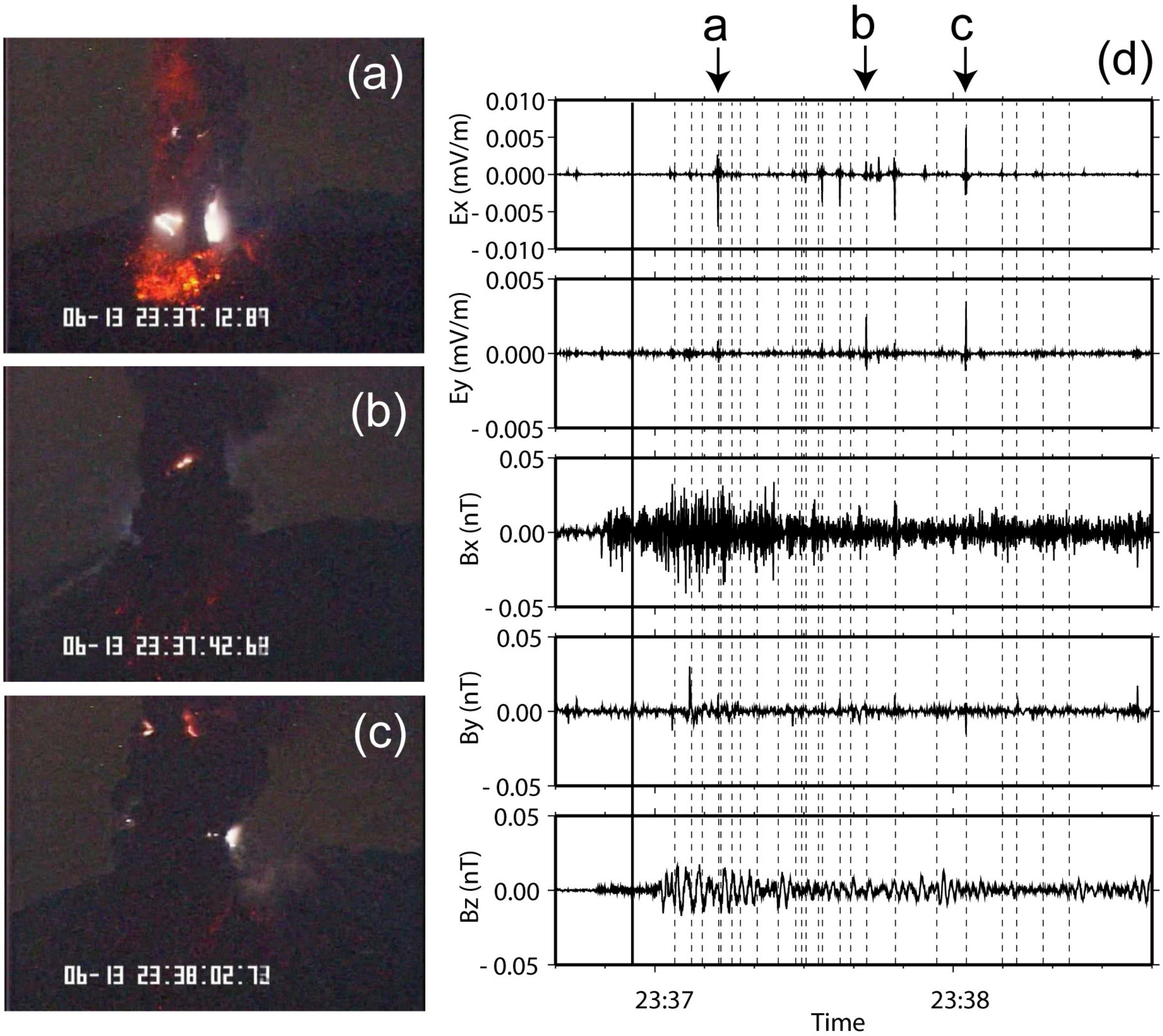

Fig. 2. Photographs of an eruption at Showa crater at 23:37 on 13 June 2008, and corresponding magnetotelluric (MT) time series recorded at HARMT. The solid vertical line indicates the time when the erupted material emerged at the crater rim. Dashed vertical lines indicate times when lightning flashes were observed in the movie.

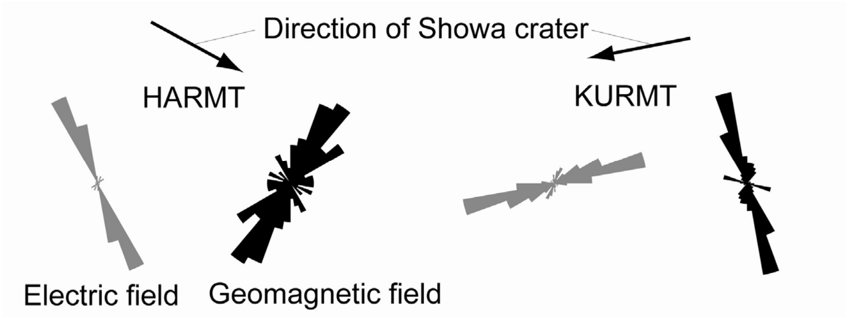

Fig. 3. Rose diagrams showing the estimated arrival directions of MT pulses.

4. Microscopic View of Particle Electrification

Various electrification mechanisms have been suggested for within volcanic plumes, including ice–hail (frozen volcanic gas) collisions, as observed in thunderstorms, groundwater–lava interaction within the volcanic edifice, collisions among ash particles, and fragmentation of magma [see the review by Mather and Harrison, 2006; James et al., 2008]. Among these mechanisms, ice–hail collision is unlikely to occur at Sakurajima because of the warm weather at the site (annual range of daily average temperature of 10–30 °C).

Figure 4 shows the relationship between the occurrence of pulses and the initial velocity of rising cloud, maximum cloud height, and maximum infrasound at Arimura (see Fig. 1 for the location). The pulses tend to occur during eruptions that emit volcanic ash to high altitudes. The initial velocity appears to have little influence on the MT pulses. Interestingly, pulses were not observed during small Vulcanian "explosions" associated with strong infrasound waves. In addition, we found no significant correlation between the occurrence of MT pulses and background meteorology, such as temperature, atmospheric pressure, humidity, and wind speed. These results suggest that the continuous collision of particles during plume growth is the dominant mechanism in producing CG lightning and the corresponding MT pulses. In the case that fragmentation of magma at eruption onset is a dominant mechanism of electrification, MT pulses should also be observed during explosive eruptions.

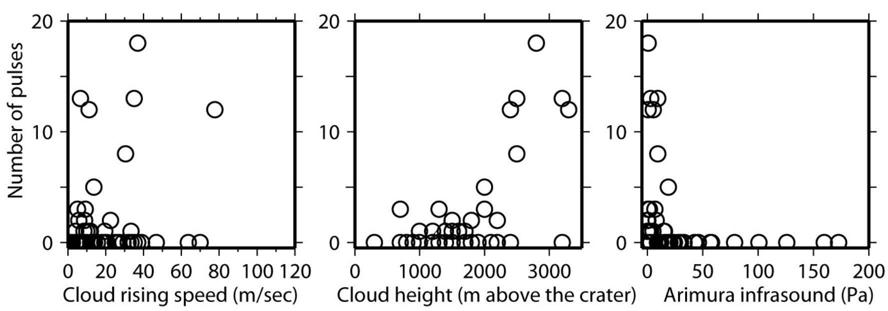

Fig. 4. Comparison of the number of pulses in each eruption with cloud rising speed, maximum cloud height, and infrasound strength. Cloud rising speed is estimated from the time that the plume rises 70 m above the crater during the initial stage of the eruption.

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References

Aizawa, K., W. Kanda, Y. Ogawa, M. Iguchi, A. Yokoo, H. Yakiwara, and T. Sugano, Temporal Changes in Electrical Resistivity at Sakurajima Volcano from Continuous Magnetotelluric Observations: Possible Indication of Lateral Magma Degassing, submitted to *J. Volcanol. Geotherm. Res.*

Anderson, R., S. Björnsson, D. C. Blanchard, S. Gathman, J. Hughes, S. Jónasson, C. B. Moore, H. J. Survilas, and B. Vonnegut (1965), Electricity in volcanic clouds, *Science, 148*, 1179-1189.

Brook, M, C., B. Moore, and T. Sigurgeirsson (1974), Lightning in Volcanic Clouds, *J. Geophys. Res., 79*, 472-475.

Hoblitt, R. P. (1994), An experiment to detect and locate lightning associated with eruptions of Redoubt Volcano, *J. Volcanol. Geotherm. Res., 62,* 499-517.

James, M. R., L. Wilson, S. J. Lane, J. S. Gilbert, T. A. Mather, R. G. Harrison, and R. S. Martin (2008), Electrical charging of volcanic plumes, *Space Sci. Rev. 137*, 399-418, doi: 10.1007/s11214-008-9362-z.

Lacks, D. J., and A. Levandovsky (2007), Effect of particle size distribution on the polarity of triboelectric charging in granular insulator systems, *J. Electrostatics 65*, 107-112.

Mather, T. A., and R. G. Harrison (2006), Electrification of volcanic plumes, Surv. *Geophys., 27*, 387-432, doi:10.1007/s10712-006-9007-2.

McNutt, S. R., and C. M. Davis (2000), Lightning associated with the 1992 eruptions of Crater Peak Mount Spurr Volcano, Alaska, *J. Volcanol. Geotherm. Res, 102*, 45-65.

Pähtz, T., H. J. Herrmann, and T. Shinbrot (2010), Why do particle clouds generate electric charges?, *Nature physics, 6*, 364 – 368, doi: 10.1038/NPHYS1631.

Thomas, R. J., P. R. Krehbiel, W. Rison, H. E. Edens, G. D. Aulich, W. P. Winn, S. R. McNutt, G. Tytgat, and E. Clark (2007), Electrical activity during the 2006 mount St. Augustine volcanic eruptions, *Science, 315*, 1097, doi:10.1126/science.1136091.

Yokoo, A., T. Tameguri, and M. Iguchi (2009), Swelling of lava plug associated with a Vulcanian eruption at Sakurajima Volcano, Japan, as revealed by infrasound record: case study of the eruption on January 2, 2007, *Bull. Volcanol., 71*, 619-630, doi: 10.1007/s00445-008-0247-5.

Yokoo, A. (2009), Continuous thermal monitoring of the 2008 eruptions at Showa crater of Sakurajima volcano, Japan, *Earth Planets Space, 61*, 1345-1350.