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Laboratory studies on electrical effects during volcanic eruptions

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Abstract
This laboratory study reports on electrical phenomena during the explosive eruption of a basaltoid silicate melt. Contact electricity is produced in the phase of thermo-hydraulic fracturing of magma during the explosive interaction with water. The electrical charge produced is directly proportional to the force of the explosion, as the force of explosion is linearly proportional to the surface generated by the thermo-hydraulic fracturing. Simulation of the ejection history using inerted gas as a driving medium under otherwise constant conditions did not result in significant electric charging. The results have the potential to explain in nature observed lightening in eruption clouds of explosive volcanic events.

Key words *experimental volcanology – explosive volcanism – magma fragmentation – contact electricity – electrical effects*

1. Introduction

Intensive volcanic explosions in nature were observed when magma comes into contact with water. To investigate this so-called phreatomagmatic explosion in the laboratory, beginning in 1986 an experimental set-up was built by Zimanowski *et al.* (1991). They melted volcanic rocks in a crucible and then injected water into the melt. Explosion of this quasi-stable premixture was triggered by an artificial shock wave. The experimental results under these laboratory conditions already showed that phreatomagmatic explosions can be modelled (Zimanowski *et al.*, 1995). Recent developments of these experiments simulated identical expansion and ejection behaviour with respect to experimental phreatomagmatic explosions (*e.g.*, particle speed and fragmentation) by the release of pressurised gas into the melt (Zimanowski *et al.*, 1997).

The goal of the experiments reported here was to investigate the effects of contact electricity between melt and water at the interactive surface during the explosive interaction.

2. Experiments

The schematic drawing of the experimental set-up is given in fig. 1. The silicate melt (140 ml) in a steel crucible is inductively heated up to a temperature of 1650 K. The crucible rests on a socket with a force transducer in between. In a horizontal distance of 1 m from the expected explosion nucleus, a electrical insulated metallic grid detector of 60 cm to 50 cm is mounted. The electric voltage between grid and crucible is detected by a voltmeter of 1000 MΩ input resistance. During the experiments, grid voltage and explosion force could be recorded simultaneously.

Two different experimental series were performed.

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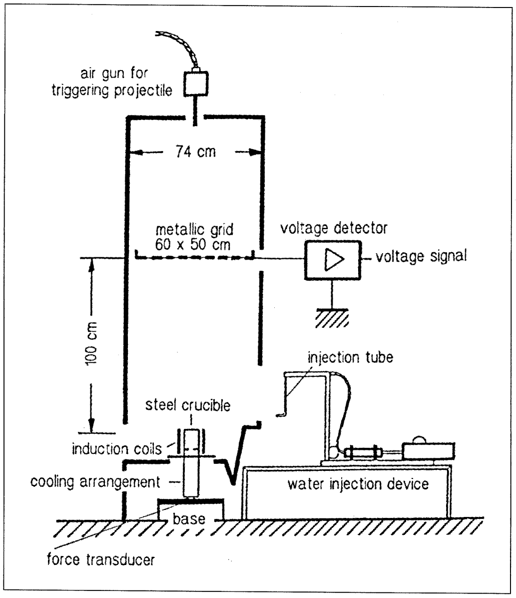

Fig. 1. Schematic drawing of explosion experiment set-up.

a) *Phreatomagmatic explosion* – At a melt temperature of 1650 K, the injection tube is moved into the melt and 15 ml of purified water are injected (fig. 2, phase II). By variation of injection speed between 1.0 and 8.2 m/s various premixes of water and melt and consequently different explosion intensities can be achieved. This hydrodynamic mixture of melt and water-domains is stable due to vapour-film boiling conditions. To trigger the explosion by a shock-wave, a projectile (less then 6 J kinetic energy) was shot onto the melt surface. The following direct contact between water and melt leads to thermo-hydraulic fragmentation and the water/melt interface starts to grow (phase III). This

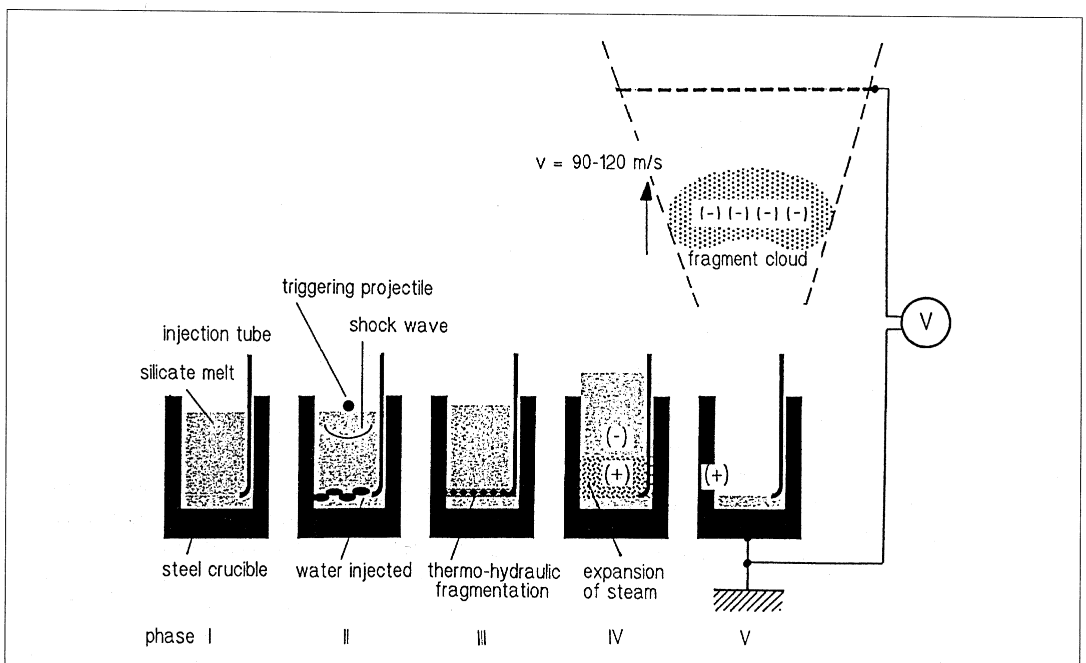

Fig. 2. Phases during experimental phreatomagmatic explosion in the crucible and detection of electrical potential at a metallic grid detector.

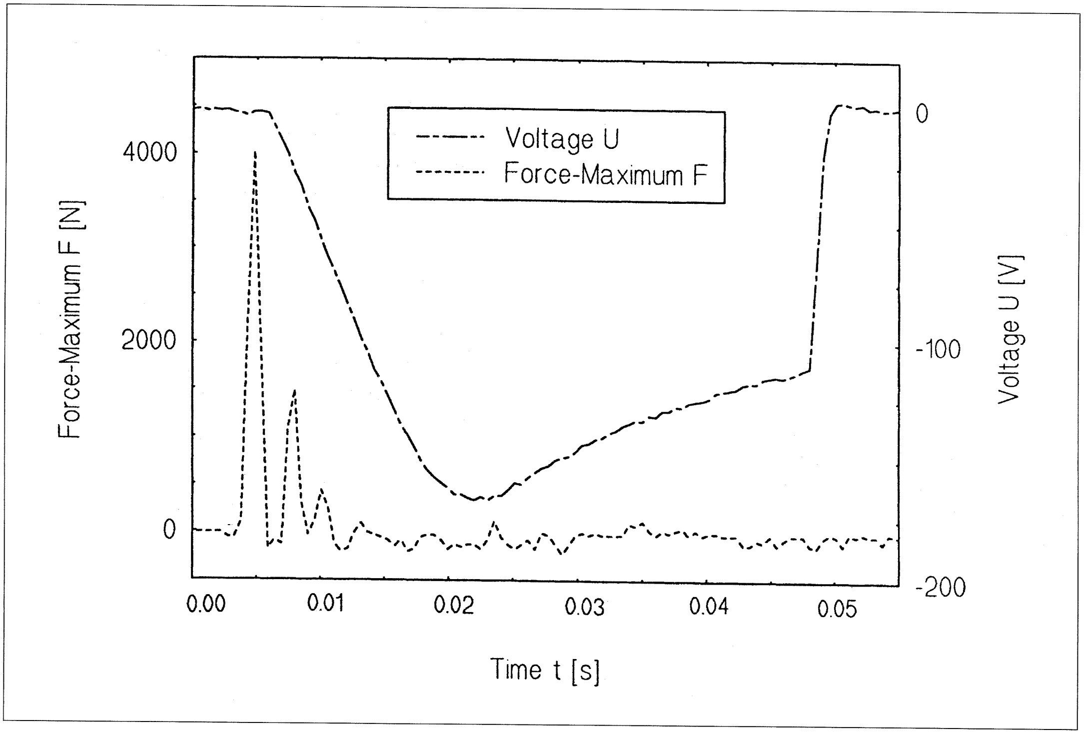

Fig. 3. Explosion force and voltage records at the detector grid *versus* time during one typical phreatomagmatic explosion experiment.

interface enlargement is terminated once the water becomes super-critical and vaporizes.

Expanding steam ejects the expanding particle cloud upwards (phase IV) with a speed of 90-120 m/s (depending on the explosion intensity). Double-layer contact between melt and water creates contact electricity and charges the melt particles negatively against the water particles. About 10 ms after explosion onset, the cloud of melt particles reaches and passes the metallic grid detector in 1 m distance (phase V). At the grid, a negative electrical potential against the steel crucible can be detected.

b) *Melt expansion by gas* – In this series of experiments, the expansion phase (fig. 2, phase IV) is reproduced by the release of a pressurised gas into the melt through the same injection tube. At otherwise constant conditions, an identical ejection history was achieved, as in the case of the experimental phreatomagmatic explosion, described above. Consequently no water-melt interface was established, and therefore no contact electricity should be produced.

3. Results

a) *Phreatomagmatic explosion experiments* – A typical relation between explosion force and voltage detected at the metallic grid is shown in fig. 3. At t = 6 ms, approximately 2 ms after explosion onset (at the moment when the steam expands and the melt begins to leave the crucible *i.e.* t = 4 ms), an increasing negative voltage was detected at the grid. In this experiment, its absolute value reached a maximum of 168 V when the particle cloud passed the grid sensor.

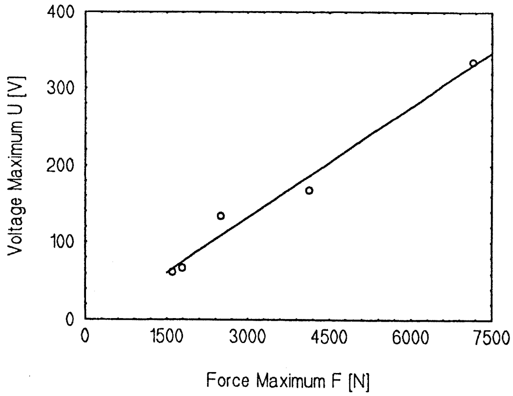

Fig. 4. Correlation between force maximum and voltage maximum during explosion experiments of various intensities.

Later the discharging curve became erratic, because water particles and returning melt particles touched the grid.

The electrical records of a series of experiments with various explosion intensities show a linear ratio between force maximum of the explosion and voltage maximum at the grid (fig. 4).

b) *Gas expansion experiments* – The record of grid voltage in fig. 5 in contrast to fig. 3 indicates a delay time in the range of about 12 ms after melt expansion onset. This corresponds to the arrival time of the melt cloud at the metallic grid. Furthermore, the voltage value was found to be only – 4.3 to – 4.5 V. This is explained to be a secondary effect of contact electricity between melt and grid.

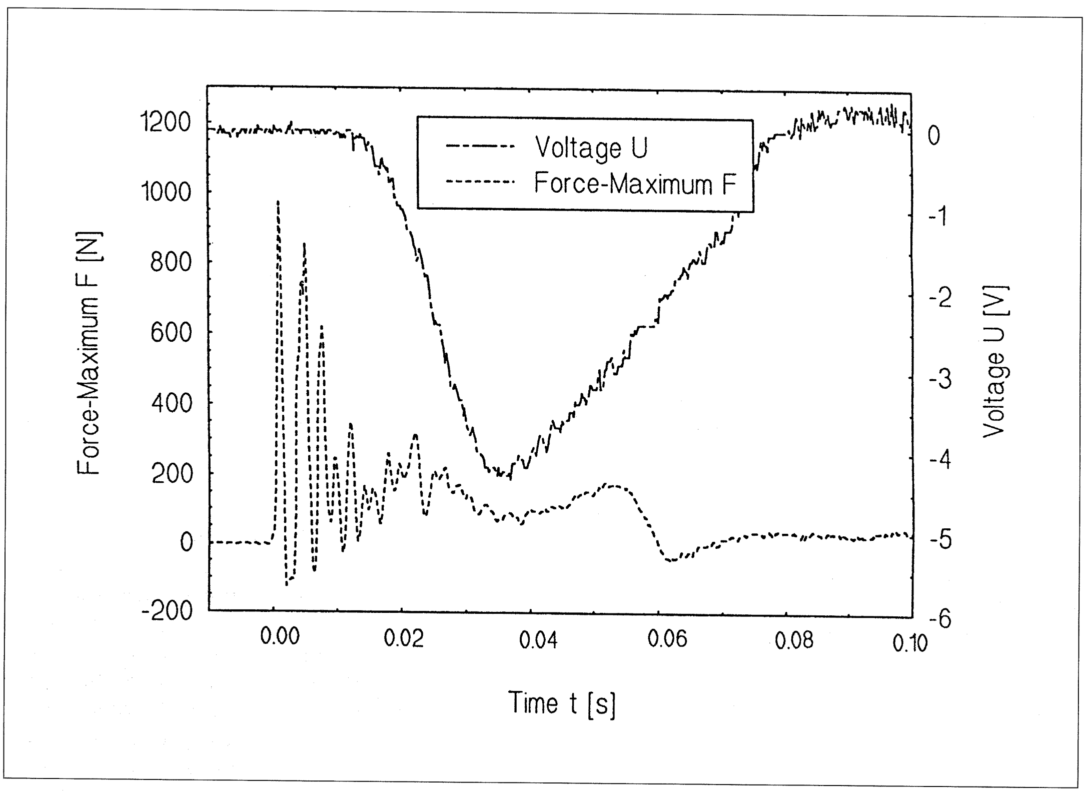

Fig. 5. Explosion force and voltage curves during one, typical gas expansion experiment.

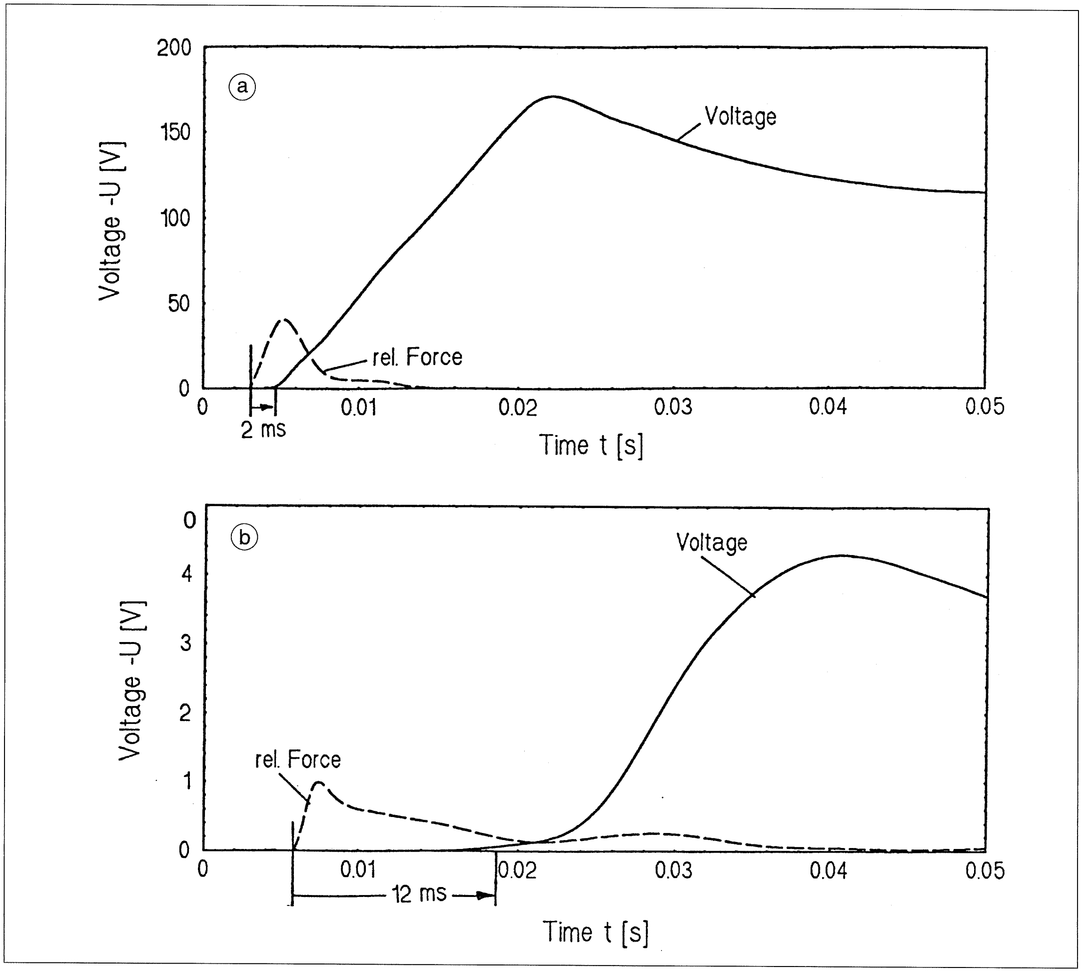

Fig. 6a,b. Comparison of force and voltage curves during phreatomagmatic explosion experiments (a) and gas expansion experiments (b).

Figure 6a,b compares results during phreatomagmatic explosion (a) and gas expanding experiments (b).

4. Interpretation and conclusions

Only in cases of phreatomagmatic explosions was a contact electricity measured. It is explained to result from the formation of a double-layer interface between silicate melt and water during the fragmentation phase. The potential of silicate melt *versus* water is negative. The total generated electrical charge Q can be calculated using the law of dielectric displacement D in a spherical surface around a punctual charge Q

$$D = Q / A , \qquad (4.1)$$

where Q is the electric charge, and A the spherical surface, and further

$$D = \varepsilon \cdot U/d \qquad (4.2)$$

where ε is the dielectric constant, U the absolute value of voltage, and d the radius of the spherical surface.

If we assume that in this experimental arrangement d is approximately the distance between explosion centre and detector grid (crucible), and A is the surface area of the detector grid, then eqs. (4.1) and (4.2) finally lead to

$$\varepsilon \cdot U/d = Q/A \,, \qquad (4.3)$$

showing that the maximum absolute value of the voltage detected, is proportional to the electrical charge produced.

Furthermore, if the electrical charge is proportional to the double-layer surface during the explosion process, then the measured voltage should be directly proportional to the surface area generated during the explosion and finally proportional to the explosion intensity.

5. Outlook

The experimental study presented here shows, that phreatomagmatic explosions have the potential to explain lightening in eruption clouds observed in nature during explosive volcanic events. Measurement of the time delay between the seismic signals picked up at the time of the explosion and electric events detected at volcanic edifices may be used to distinguish between two-layer explosion processes (*e.g.*, water to magma) and magma ejection by non-ionized gas.

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