WATER AND THE GENERATION OF VOLCANIC ELECTRICITY

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ABSTRACT

Electrical measurements, made both in the laboratory and at Surtsey volcano, have indicated that highly charged clouds are generated when water comes into contact with molten lava. An examination of the literature has revealed a number of cases where electrical activity in volcanic clouds appeared to be caused by this process. The significance of this charge generation mechanism, as opposed to others that undoubtedly operate in volcanic eruptions, remains to be established.

1. INTRODUCTION

References to lightning in volcanic eruptions can be found in the literature going back many hundreds of years. But few electrical measurements have been made, and most descriptive accounts, though possibly accurate, portray such a complex picture that it is impossible to arrive at any conclusions concerning the origin of the charge.

Volta [16] was probably the first to advance a hypothesis of volcanic electricity that was based on experimental fact. He discovered that the combustion of various materials produced an electrically charged smoke, and concluded that combustion within a volcano was the cause of the charge that produced the lightning in volcanic clouds. Williams [17], after carrying out his own experiments, arrived at the same conclusion. This was a logical one as it was commonly accepted in their day that combustion processes occurred within active volcanoes.

Volta also discovered that water which came into contact with a hot surface produced a charged cloud. He attributed this to charge generation by evaporation. Shortly after this, de Saussure repeated and enlarged on this experiment, as reported by Adams [1], and concluded that the intense charge in volcanic clouds was probably generated when water within the volcano made contact with the hot material. de Saussure [8] later made the admirable suggestion that one should make electrical measurements near an erupting volcano to determine whether the clouds carried a positive or negative charge. This suggestion is still pertinent today.

It appears that de Saussure's idea on the generation of volcanic electricity was not considered again until recently. In the laboratory Blanchard [6] was able to generate positively charged clouds by dropping sea water onto molten lava or other sufficiently hot materials. He suggested that a similar process could occur in nature if the magma from erupting oceanic volcanoes made contact with sea water. The eruption of Surtsey volcano in the sea south of Iceland provided an opportunity to test this and other hypotheses of volcanic charge generation. It was found [2] that a net positive charge was being ejected from the crater during the explosive phase of the eruption. The explosions appeared to be caused by sea water pouring into the crater and striking the hot magma. It could not be proved, but presumably the charge was being generated at the same time. In a later phase of the eruption sea water no longer had access to the crater. A lava lake formed. Streams of lava eventually flowed into the sea, producing long plumes of dense, white cloud. These clouds carried a positive charge which clearly was being generated at the point of contact of the lava with the sea [5]. This generation of charge cannot be explained (as thought by Volta) by evaporation per se. Rather it appears to be associated with the generation of micro -sized drops of sea water or sea-salt particles [5].

The laboratory experiments [5] have shown that charged clouds are also produced when far less saline solutions than sea water make contact with molten lava. This suggests that the phreatic explosions which occur when ground water, lake or river water, and glacial melt water strikes molten lava will produce electrical activity.

Undoubtedly there are several mechanisms by which charge can be generated in volcanic clouds, either operating together or separately. But our work in the laboratory and at Surtsey has shown that the water mechanism can be of significance by itself, and has prompted us to examine some of the literature and reports of past eruptions. The rest of this paper will be devoted to a brief account of investigations of other volcanic eruptions where the contact of water with molten lava may have been responsible for some or all of the electrical activity that was observed. We make no claim to having done a complete literature search; no doubt many other such investigations have been published.

2. ELECTRICAL EFFECTS IN VOLCANIC ERUPTIONS

MARINE ERUPTIONS

In June 1811, Captain Tillard, commanding the British sloop *Sabrina*, came across a volcanic eruption in the sea just off the island of São Miguel in the Azores. On June 14, from a high cliff on São Miguel, he was able to watch the eruption that was less than 2 km. away [15]. On that day he witnessed an extraordinary and spectacular event, the birth of an island. "Soon after our arrival on the cliff, a peasant observed he could discern a peak in the water: we looked, but could not see it; however, in less than half an hour it was plainly visible, and before we quitted the place, which was about 3 hours from the time of our arrival, a complete crater was formed above the water, not less than 20 ft. high on the side where the greatest quantity of ashes fell; the diameter of the crater being apparently about 400 or 500 ft." During this time there were numerous explosions in which a mixture of tephra and cloud was ejected upward at high speeds. The tephra attained heights of about 300 m. while the cloud columns went much higher. In the course of these explosions ". . . the most vivid flashes of lightning continually issued from the densest part of the volcano."

A similar account was given by John Davy [7] of a volcano in the sea off the southern shore of Sicily. Davy visited the volcano by boat, and his account of the eruption and lightning was remarkably similar to Tillard's and to what we observed at Surtsey in the explosive phase of the eruption [2].

LAND ERUPTIONS

Palmieri [11], probably the first to obtain atmospheric-electric data near a volcanic eruption, made some interesting observations during an eruption of Vesuvius in 1872. He found that steam clouds alone carried a positive charge, ash clouds alone a negative charge, and both signs of charge with steam and ash mixed.

Among the numerous Japanese investigations into volcanic electricity, the work of Ishikawa et al. [9] at the volcano Azuma is of interest from the viewpoint of the present paper. The volcano was relatively quiet but had been in violent eruption several months before. They measured the potential gradient and space charge in the volcano "smoke." Both were positive. The space charge, measured about 300 m. from the crater, was of the order of 10^4 elementary charges $cm.^{-3}$ The "smoke" was presumably a water cloud for they remarked that it was white and "looked like a steam jet and was supposed to contain a very small amount of solid particles."

Many volcanoes contain crater lakes. During an eruption we might expect electrically charged water clouds to be generated by interaction between the water and the magma. Such may have been the case during the first phase of the 1902 eruption of the volcano Soufrière [3]. Prior to the eruption its crater lake, at an altitude of 590 m., was about 800 m. in diameter and about 160 m. deep. Immediately before the eruption the lake was observed to be boiling. During the first hours "columns of white vapour" rose to altitudes of several thousand feet. The activity became heavier and some hours later ". . . there was thunder and lightning, showers of black and heavy material could now be seen thrown outwards and falling downwards from the column of whitish vapour, associated with loud noises and more violent outbursts." This description is reminiscent of what was observed at Surtsey where the contact of sea water with the magma presumably generated the charged clouds [2].

Explosive volcanic eruptions in Iceland are many and varied. Some, such as those at Hekla and Askja, are caused by magma which is of the explosive type (acid, high viscosity, and high gas content) while those at Surtsey, Katla, and Grímsvötn are caused by phreatic explosions, the contact of water with magma that otherwise is not explosive (basic, low viscosity, and low gas content). Katla and Grímsvötn are sub-glacial volcanoes whose eruptions, like those at Surtsey, are accompanied by strong electrical activity and frequent lightning in the eruption cloud.

Although the initial phase of the eruption of the volcano Hekla and also that of Öraefajökull (under Vatnajökull glacier) is caused by an explosive type magma, water may, at times, also play a role in the explosions. Öraefajökull is ice capped and its eruptions are accompanied by floods of water that are released by the melting of the ice of the glacier. Hekla may sometimes be covered with ice. The very first phase of its last eruption in 1947 consisted of an extremely violent expulsion of water vapor along with a flow of water which rushed down the northwestern slope of the volcano. But in contrast to the Surtsey-Katla-Grímsvötn eruptions, lightning is not often associated with the eruptions of Hekla and Öraefajökull.

LAVA-WATER CONTACT OUTSIDE CRATER

Lightning has been observed in the cloud plumes which rose from the point where streams of lava came into contact with sea water. This observation was made by Jaggar [10] when an aa-type lava flowed 14 mi. down the slopes of the Hawaiian volcano Mauna Loa and plunged into the sea. "The uprush of steam where the lava made contact with the sea carried up rock fragments and sand and built a black sand cone. The lava 'rafts' or blocks of bench magma which rolled down the live channel, were seen to bob up, make surface steam, and float out some distance from the shore without sinking at first, as though buoyed by the hot gas inflating them. Lightnings were seen in the steam column."

An analogous observation was made after the eruption of the Soufrière volcano [3] when hot sand and ash flowed from the crater down into the ravines on the flanks of the volcano. An observer noted that "Occasionally discharges of vapour would take place from the furthest first-mentioned ravine, and each was accompanied by a flash and peal of lightning and thunder." Anderson and Flett [3] believe the vapor discharges were caused by rainfall runoff coming into contact with the hot sands.

Lightning in clouds that were produced when glacial melt water came into contact with streams of molten lava was observed during the great fissure eruption of Lakagígir in Iceland in 1783–1784. An account of this eruption was written by the parson, Jón Steingrímsson [12, 14], who witnessed most of the events that he described. The eruption was one of the greatest in historic times; the erupting fissure was 25 km. long and had about 100 active craters. Lava streams covered an area of 565 $km.^2$, and the volume of the erupted material has been estimated at about 12 $km.^3$ These streams rushed to the lowlands through canyons eroded by rivers which drained the glaciers. The glowing lava was flooded and the water boiled. White plumes of cloud rose from the canyons and the sides of the lava streams. Amidst strong clashes of thunder, rain poured down from these clouds [12].

3. DISCUSSION

Explosive activity in craters erupting basaltic magma of low gas content and low viscosity is difficult to explain unless one assumes that the explosions are caused by the direct contact of ground water with the magma. According to the evidence from Surtsey [2] and laboratory investigations [5] we may therefore expect that most phreatic eruptions of basaltic magma will generate strongly charged volcanic clouds.

The marine eruptions described by Tillard [15] and Davy [7] resemble those seen at Surtsey [2]. It seems probable that these were phreatic explosions and it is more than likely that the charge for the lightning was generated at the same time.

The electrical investigations on the water clouds that rose from the craters of land volcanos [9, 11] were interesting in that they showed that the clouds carried a positive charge. If a sufficient amount of ground water was present it is possible that the charged clouds were generated when this water made contact with hot material within the crater. In the case of the volcano Azuma [9] the ground water may have been supplied by two small lakes that were about 1200 m. from the crater and at about the same elevation. Alternatively, one might argue that these clouds evolved from water released from magma deep within the crater. However, at Surtsey the clouds ascending from boiling lava craters were not found to carry any significant charge.

The highly charged eruption clouds from the Icelandic sub-glacial eruptions quite possibly were generated when glacial melt water made contact with the magma. This is made even more plausible in view of the laboratory studies. Positively charged clouds were generated when drainage water from the Mýrdalsjökull and Vatnajökull glaciers (both in Iceland) was dropped onto samples of molten lava [5].

Thorarinsson [13], who has examined the literature, both published and unpublished, for observations of lightning in the eruption clouds of Icelandic volcanoes, has this to say. "From what I have compiled regarding electrical phenomena connected with volcanic eruptions in Iceland, I am not going to draw any certain conclusions. It seems rather clear, however, that the submarine Surtsey eruption, during the explosion phase of which magma was in contact with salt water, does not differ in any degree from the Katla and Grímsvötn eruptions with regard to the occurrence of lightning in the eruption column, although in the case of Katla and Grímsvötn the magma is in contact with fresh water. The chemical composition of the magma feeding these three volcanoes is rather similar. On the other hand it seems clear that in spite of great tephra production at times the lightnings are much more scarce in the Hekla eruptions than in Surtsey-Grímsvötn-Katla eruptions. The difference is particularly striking as regards the violent initial phase, when the tephra uprush is at its maximum. Maybe the chemical composition of the tephra here plays a role as the initial products of Hekla are much more acid than those of the other volcanoes. I remember, however, the beautiful lightning pictures of the eruption cloud of the Komagatake 1929 eruption I saw in Japan and that tephra was highly acid." Although Thorarinsson appears to subscribe to the role of water in the generation of electricity in some eruptions, he points out the possibility that the relative lack of lightning in the Hekla eruptions may be due to the nature of the magma, and not to the relative absence of water.

There is no doubt that the contact of water with hot lava outside the crater can generate highly charged clouds [5], but despite many observations of this type of charged cloud at Surtsey there are no known reports of lightning. There was, however, frequent lightning in the clouds that rose from the crater during the phreatic phase of the eruption [2]. Perhaps the lack of lightning is because these clouds were smaller than those ejected from the crater. Thus, in spite of a high charge density the potential gradient did not attain a high enough value to produce lighting. The three cases that have come to our attention in which lightning was reported in clouds generated outside the crater are no doubt those in which the lava-water contact area was very large. In addition the charge density, because of differences in the nature of the lava and the manner in which it made contact with the water, may have been greater than that at Surtsey. Both factors may have been present in the case reported by Jaggar [10]. In a detailed account he told of how a river of aa-type lava some 100 m. wide plunged over a cliff of several meters height and into the sea. The observations of Steingrímsson [12] reported by Thoroddsen [14], though not so well documented, clearly involved extensive lava-water contact. But the mention of rain with the lightning suggests thunderstorm activity. It is likely that the storm was initiated and fed by the large amounts of water vapor and charge that were generated when the glacial melt water made contact with the lava streams.

It is possible that both signs of charge could be found in an eruption cloud even though it was generated by the lava-water contact process. Recently Björnsson [4] measured the potential gradient at the surface of the sea near the eruption plume of an oceanic volcano located near Surtsey. The plume appeared to carry a positive charge, for the potential gradient was positive and far exceeded the fair-weather gradient. But he found that the tephra (largest particle 5-mm. diameter) which fell just downwind from the crater carried a negative charge. He suggested that the charging of the tephra might have occurred in the eruption column as drops of sea water struck the glowing particles. A positively charged cloud would be produced which would continue to rise. The negatively charged tephra particles would soon fall out to the ground.

4. CONCLUSION

Undoubtedly there are a number of mechanisms by which charge is generated in volcanic clouds. The contact of water with molten lava, or any volcanic material that is sufficiently hot, is one of them. This mechanism may, in some cases, play a major role in the charge generation not only in oceanic volcanic eruptions but also those on land. Further information on this problem will be obtained only by making measurements of potential gradient and charge carried by erupted particles near a number of volcanic eruptions, both phreatic and nonphreatic, marine and terrestrial.

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