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CURRENT PROBLEMS IN RESEARCH

Electricity in Volcanic Clouds

Investigations show that lightning can result from charge-separation processes in a volcanic crater.

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On the morning of 14 November 1963, volcanic eruptions were observed in the Atlantic Ocean at about latitude 63°18′N and longitude 20°37′W, 23 kilometers southwest of Vestmannaeyjar, off the southern coast of Iceland in water 130 meters deep. Within 10 days an island formed that was nearly 1 kilometer long and about 100 meters above sea level. This island, shown in Fig. 1 as it appeared in late November of 1963, has been named Surtsey by the Icelandic Government.

One of the first U.S. scientists to view the volcano was P. S. Bauer of American University. On 28 November Bauer observed it at close range and noted spectacular lightning discharges in the cloud that it produced. His description of this electrical activity prompted the American authors of this article to visit Iceland and to join the Icelandic scientists who were already studying Surtsey.

During November and December of 1963, Th. Sigurgeirsson of the University of Iceland took time-lapse motion pictures of the eruption from his laboratory at Reykjavík, 114 kilometers to the northwest. In many of these pictures the eruption clouds can be seen to rise almost vertically to a maximum altitude of about 9 kilometers. The average rate of rise of the cloud top is estimated to be about 12 meters per second between the altitudes of 7 and 9 kilometers. After reaching their maximum altitudes the cloud turrets usually fell back to a lower level, forming a stratiform layer that was blown away by the strong winter winds. The height of the tropopause during this period was about 10.5 kilometers.

A vivid display of lightning occurred in early December when, apparently, thunderstorms were initiated by the eruptions. Time-exposure photographs of the cloud over the volcano were taken from Vestmannaeyjar on the night of 1 December (see Fig. 2 and cover). During this period intense lightning illuminated the volcanic cloud almost continuously, and large dust particles from the volcano were transported by the wind to Vestmannaeyjar. When these pictures were taken, the moon was full and to the left of the cloud, out of view of the camera. Presumably the featureless luminosity of the sky and the cloud edges in these figures is a result of moonlight.

The eruptions continued with varying intensity into January 1964, and strong whirlwinds were frequently observed beneath the eruption clouds. In mid-January the first volcanic crater became plugged, and Surtsey was dormant for a short time. A new fissure then opened to the west of the first crater, and violent eruptions again were seen. During the late winter the air over this portion of the North Atlantic was thermally stable; no more thunderstorms were observed near Surtsey, although lightning frequently occurred when the eruptions were vigorous.

Lightning associated with volcanic eruptions has often been reported in the past (*1*, *2*), but there has been little opportunity for investigators of thunderstorm electricity to study the phenomenon. Some of the recent reports described measurements of atmospheric electricity made downwind of several volcanic eruptions in Japan (*3–5*). It was found that these electrical disturbances were different in several respects from those produced by thunderstorms; thus we welcomed the opportunity presented by the Icelandic eruption. The U.S. members of the group joined the Icelandic scientists and began observations of the electrical phenomena in February of 1964.

In early February there was a deep low-pressure weather system to the west of Iceland, so that east and southeast winds blew past Surtsey. On a flight to Iceland from Newfoundland we detected high-level dust layers several hundred kilometers downwind of Surtsey, and the concentration of dust and haze increased appreciably as we approached the volcano. The sunsets over this part of the North Atlantic during this period were deep orange and even brown in color, apparently as a result of the eruptions.

Observations of 5 February 1964

Our first observations near the volcano were made on the afternoon of 5 February from the fishing vessel M.S. *Haraldur*. A portable electrome-

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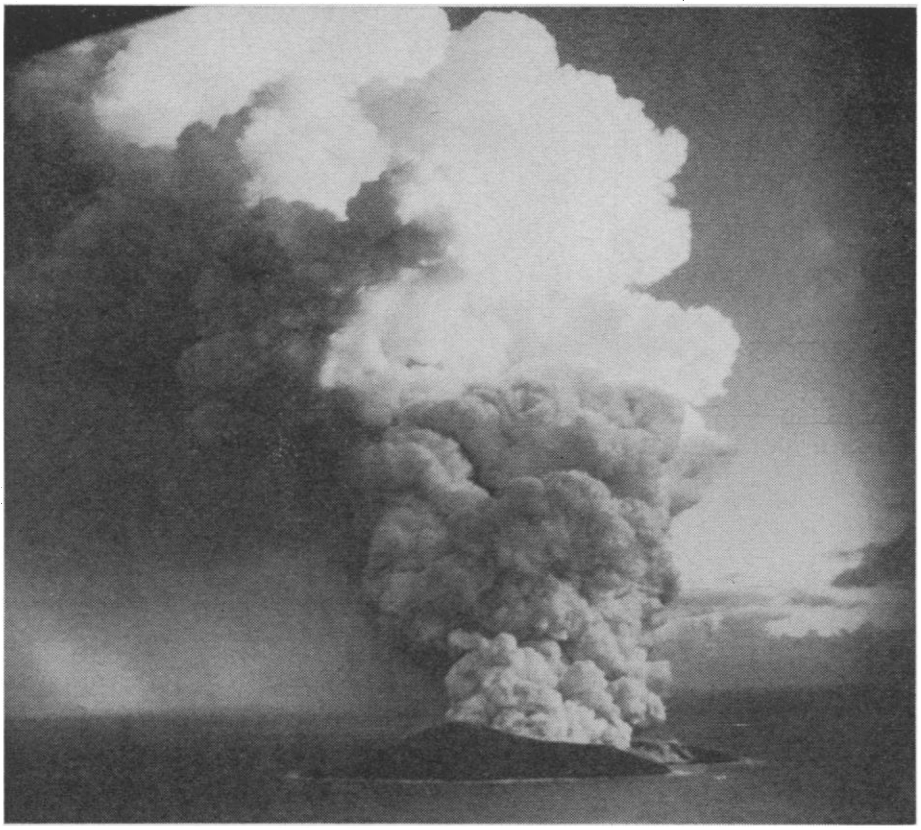

Fig. 1. Aerial view of Surtsey as it appeared on 5 December 1963. [S. Thorarinsson]

ter and a radioactive (polonium) probe were mounted on an insulator above the deckhouse to measure the potential gradient. No recording meter was available for making a continuous record, so the data were taken intermittently.

At 1400 Icelandic Mean Time (*6*) the boat was about 6 kilometers north of the island, the wind was very light, and there was a thin overcast. The plume of cloud from the volcano was rising almost vertically, with a slow movement to the west. At this time the potential gradient, which, during the approach to the volcano, had become increasingly intense in the positive direction (the usual fine weather condition, with positive charge overhead) for a short time became negative. This reversal may have been related to a very light rain of drops, black with tephra, that fell on the boat a few minutes later. As we approached the volcano, the gradient became increasingly intense in the positive direction, until at 1450 hours, when the *Haraldur* stopped 200 meters northwest of the island, it was at least 10 times the gradient measured under conditions of undisturbed fine weather (the "fine weather" value).

During this period there were almost continuous eruptions of steam from one vent within the crater, fountains of molten lava from another vent, and a succession of whirlwinds that descended from the volcano cloud (*7*), but no lightning was observed.

Finally, at 1535 hours, there was a brief period of more intense eruptions of steam and tephra, accompanied by several lightning sparks. Following the lightning, the gradient briefly became negative again and then resumed a steady large positive value. Just after nightfall there was a large increase in the intensity of the eruptions, and the lightning frequency rose to about ten discharges per minute. Unfortunately, no further electrical measurements could be made, for the electrometer insulation had become wet with sea spray.

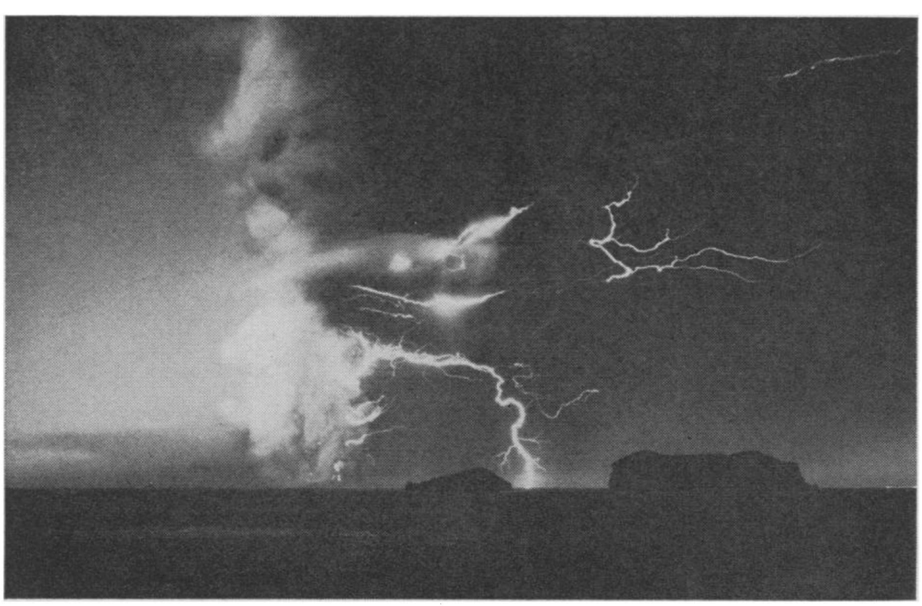

Fig. 2. Lightning in the volcano cloud over Surtsey at 1938 to 1948 hours I.M.T. on 1 December 1963 (600-second exposure). The portion of the cloud shown at top of picture is estimated to be about 8 kilometers above Surtsey. [S. Jónasson]

Aerial Observations

Some of our group made flights near the volcano in a Constellation airplane equipped by the U.S. Naval Research Laboratory with electric-field meters in the wing tips. The results of the four flights made on 11, 12, 15, and 16 February are summarized in Table 1. No indications of lightning were detected during any of the airplane flights over the volcano.

The first flight differed from the other three, both in flight pattern and in the appearance of the volcano cloud. The cloud formation on this day consisted of an active, isolated, but well-developed cumulus complete with a small anvil-shaped top. The height of the cloud top varied in a pulsating manner from about 3 kilometers to above 6 kilometers; the period of these pulsations was between 4 and 8 minutes. The pilot made successive passes, intending to fly over the cloud top, but the upward pulsations of the cloud caused about half the passes to be over smaller cells rather than over the main turret. These overflights were valuable, as they yielded an indication of the charge existing in upper regions of the cloud. A net positive charge was indicated in the cloud throughout this flight.

The second flight was made when there was a stratus overcast at 600 meters above sea level and limited visibility below; the volcano cloud was confined below the overcast layer. Three horizontal passes were made at an altitude of 400 meters, paralleling the plume as it drifted downwind. The measured horizontal fields again indicated positive charges in the cloud.

On the flight of 15 February the sky was clear, and the volcano periodically produced clouds shaped roughly like cylinders of 0.5-kilometer radius and heights of 3 or 4 kilometers. The clouds drifted downwind in a cloud street, with clear air spacing of about 1 kilometer between them. Measurements, taken alongside these clouds, of the horizontal component of electric field indicated that some of the clouds were electrically neutral but that others had a fair amount of positive charge. Later in the flight close approaches were made to the erupting crater at altitudes of 300 to 600 meters. On one pass by the crater, at an altitude of 500 meters, the crew of the airplane observed rocks, estimated to be larger than 30 centimeters across, rising above them as the volcano erupted. The spatial distribution of charge was observed to be small; the "spike" on the horizontal-field record always indicated a narrow region of positive charge over the crater. Values of the field maxima observed during these passes are shown in Table 1.

In the final flight, of 16 February, the airborne group reached the area of the volcano just after another group of us on the *Haraldur* and near the volcano had observed a large eruption and a potential-gradient perturbation unaccompanied by lightning. As the airplane flew past the crater at an altitude of 1800 meters the airborne group observed black clouds of tephra carried above them by the eruptions. The flight pattern again consisted of level passes parallel to the plume downwind of the crater, at an altitude of 1800 meters. As shown in Table 1, the net positive charge decreased rapidly as the cloud was carried away from the vicinity of the crater by the wind. The volcano temporarily ceased its eruptions soon after the pilot began following the last large cloud, and it was possible to study the decay of its charge as a function of time.

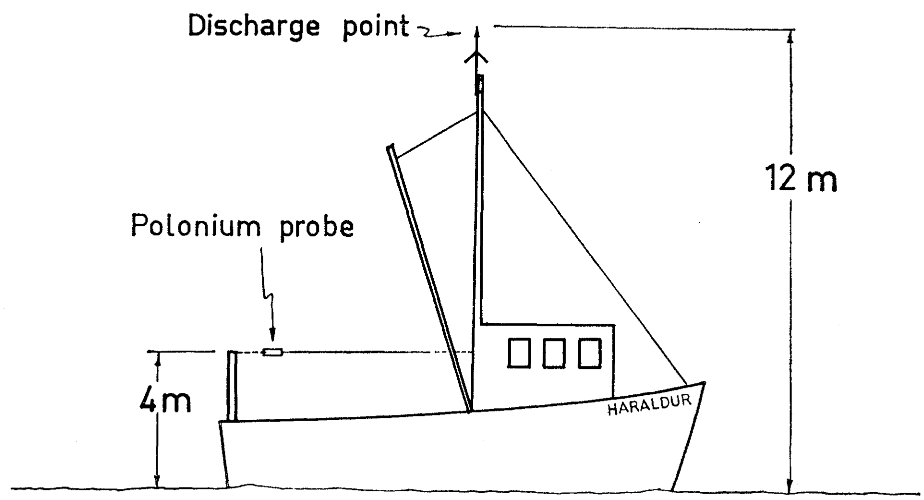

Fig. 3. Arrangement of the potential-gradient probe and the corona point for atmospheric electrical measurements from the *Haraldur* on 16 February 1964.

Another pass was made, beside and through the volcanic cloud, 5 hours later, after the sun had set; low concentrations of positive charge were then observed. The eruption activity was weak, and a red lava glow could be observed in the crater. The airplane penetrated the cloud downwind of the crater, and a spectacular display of Saint Elmo's fire was observed, with 5-meter streamers appearing on the nose of the plane. Although the charge on the airplane attained high values, the electric fields within the cloud were small. The cloud, penetrated at 1832 hours, towered above the aircraft, which was at 2300 meters above sea level.

On the flight of 16 February, not

Table 1. Maximum electric fields observed from the airplane flying by the volcano cloud on 4 days in February 1964.

Time (I.M.T.)	Airplane altitude (m)	Position relative to cloud	Electric field* (v/cm)	
		11 February		
1617	3800	Over top	>110	(E_z)
1623		Beside main cloud top	62	(E_y)
1628		Over top	15	(E_z)
1633		Over top	2	(E_z)
			12	(E_z)
		12 February		
1450	370	320 m†	26	(E_y)
	370	1000 m	39	(E_y)
	330		25	(E_y)
		15 February		
1009	300	100 m	1	(E_y)
1049	600	150 m	2	(E_y)
1050	600	150 m	1	(E_y)
1055	600		> 11	(E_y)
1100	600		8	(E_y)
1105	600	~ 10 m	6	(E_y)
1111	300	500 m	8	(E_y)
1116	300		> 11	(E_y)
1121	300		13	(E_y)
1123	300		9	(E_y)
1130	300		49	(E_y)
		16 February		
1323	1800	800 m	180	(E_y)
1330	1800	~ 500 m	300	
1334	1800	500 m	29	(E_y)
1340	1800	500 m	14	Following
1344	1000	500 m	5.2	the cloud
1353	600	500 m	4.1	downwind
1402	300	500 m	3.7	

* E_z, vertical component of the field; E_y, horizontal component normal to the cloud surface. † Meters distant from cloud.

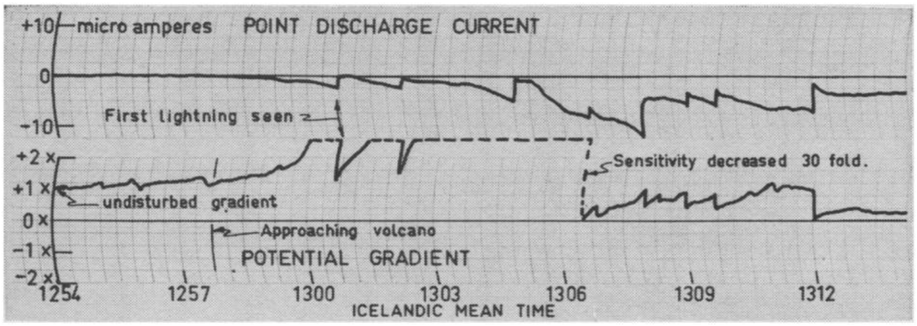

Fig. 4. Strip-chart record of potential gradient and point discharge current obtained from the *Haraldur* upwind of Surtsey on 16 February 1964.

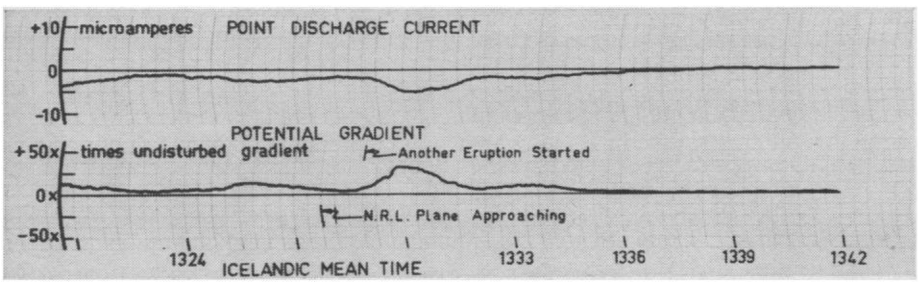

Fig. 5. Strip-chart record obtained from the *Haraldur* upwind of Surtsey as the Naval Research Laboratory airplane flew past the crater on 16 February 1964.

only were electrical measurements made but samples were taken of the atmospheric aerosols produced by the volcano. The results of the analysis of these samples will be reported elsewhere (*8*).

Observations of 16 February 1964

Four of us visited Surtsey on 16 February aboard the *Haraldur*, this time with recording equipment for measuring the electric potential gradient and point discharge currents (see Fig. 3). The polonium probe used in the potential-gradient measurement was shielded by the mast and boom above it. For this reason the potential gradients indicated during the fine-weather conditions over the open ocean away from the volcano were appreciably lower than those usually measured with more exposed probes aboard ship. However, the 85-minute voyage from Vestmannaeyjar to Surtsey gave us the opportunity to obtain a representative value of the system response to the fine-weather gradient, and we have used it in our estimates of the disturbances produced by the volcano.

The island was about 170 meters high during the period of this visit; the crater was still open to the ocean and was flooded continually with sea water. No molten lava was seen, although red glows were observed in fountains of spray cast up by falling rocks.

The volcano was erupting vigorously as the *Haraldur* approached, and large black clouds were rising rapidly. A sharp noise like the firing of artillery was heard at intervals; this was identified as thunder, for it followed visible lightning by 2 seconds or so. A tracing of the strip-chart recording obtained during the initial approach at 1257 hours is shown in Fig. 4. The potential gradient began to increase, and a flow of negative charge into the atmosphere from the exposed point commenced while the *Haraldur* was more than 1 kilometer distant from the island. As the *Haraldur* approached closer, the gradient trace went off scale in the positive direction, while the eruption continued. Lightning was then observed, and the indicated gradient decreased abruptly to about the fine-weather value observed during the voyage to the volcano. A similar decrease in the point discharge current was indicated by the trace (Fig. 4). The gradient and point discharge current then increased until the next discharge occurred; the abrupt decreases again were observed, and the chart record developed a sawtooth appearance. Ejection of black clouds continued at a lesser rate until about 1335 hours, although lightning ceased after the discharge recorded at 1312. A flow of negative charge into the air from the exposed point continued until about 1337.

The Naval Research Laboratory airplane arrived over Surtsey at about 1328, just as a vigorous eruption occurred that increased the gradient (as measured from the boat) to about 30 times the fine-weather value. A tracing of the chart record obtained aboard the *Haraldur* during this period is shown in Fig. 5. As reported above, the airborne group followed and studied the cloud that produced this disturbance; no lightning occurred during this period.

After 1335 hours the volcano became quiet, and there were no eruptions until after 1500. During this period the *Haraldur* was brought to within 100 meters of the crater. Although white and billowing clouds were frequently emitted during this period of quiescence, no electrical disturbances were recorded.

A new, more violent series of eruptions began at 1504. Black clouds were again ejected and rose at initial speeds of up to 100 meters per second; the tops of new jets often rose from sea level to the height of the island summit in about 2 seconds. The upper and outer portions of these black clouds usually turned white suddenly (see Fig. 6) after reaching altitudes estimated at 700 to 1000 meters, and the black appearance of their tops soon vanished completely. Frequent lightning was again observed; it followed new eruptions of a black cloud by about 10 to 60 seconds. Portions of the discharges were often visible at altitudes of about three island heights. Many of the discharges observed were clearly between the cloud and the earth. Occasionally lightning was observed to strike the island at some distance from the crater, but most of the discharges seemed to terminate near the source of the eruptions.

In motion pictures of the volcanic activity taken from close range at 24 frames per second, we have found two different eruption sequences in which lightning can be seen to flash about 10 seconds after the start of the eruption. We have been able to determine the approximate scale of the pictures in these sequences from the height of the island, which also appears, and in Fig. 7 we have plotted the height of the clouds for both eruptions as a function of time. In case 1 the camera was not started until after the eruption had begun, so we have extrapolated to the beginning of the eruption, as is indicated by the dashed portion of the curve.

The characteristic short, sharp crack of thunder was heard for every discharge seen and for about twice that number that were not seen. The lightning and thunder were noted to occur while most of the solid material ejected was still airborne and while much of it was moving upward.

Twenty-six discontinuities (of the type produced by lightning) were counted on the recorder chart shown in Fig. 8, covering the period between 1516 and 1536 hours; during the most vigorous eruptions five discharges were recorded in 135 seconds. The shortest interval between discharges was 11 seconds. In another portion of the chart, 13 indications of lightning were recorded in 9 minutes.

The greatest potential gradient observed was about 60 times the fine-weather value recorded during the voyage to the island; it was developed at 1527 hours, just before a lightning discharge and 34 seconds after an earlier discharge. Most of the potential-gradient maxima were about 30 times this fine-weather value, and they appear to be limited, approaching an asymptote. The point discharge trace, on the other hand, usually shows a continued increase until a discharge occurs.

An attempt was made to pass under the cloud with the boat, so that measurements could be made downwind of the volcano. As this was considered too hazardous by the boat crew, a series of measurements at successively greater distances upwind from the volcano was made, starting at 1600 hours, while the eruptions and lightning continued. No reversal in polarity of the potential gradient or of the point discharge current was observed at any time upwind of Surtsey as we receded from it. The flow of negative charge from the exposed point continued until the *Haraldur* was at a distance estimated to be about 2.6 kilometers from the island.

Observations of 22 March 1964

A further series of observations of surface potential gradient was made near the volcano, with the same instruments, by Björnsson, a member of our group, aboard an Iceland Coast Guard ship. On the morning of 22

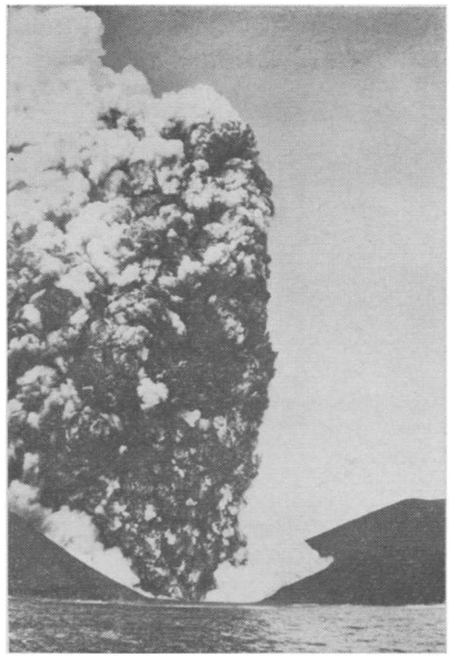

Fig. 6. Eruption of black tephra cloud carried on superheated steam (1 March 1964). The cloud abruptly turned white as the steam cooled and condensed. [S. Jónasson]

March, when the ship was 63 kilometers from the island, periodic increases in the potential gradient in the positive direction were observed; these presumably were produced by the volcano, which was continuously erupting and producing a plume 3 kilometers high in an otherwise cloudless sky. The surges in potential gradient had an irregular period of a minute or so and increased in magnitude as the ship approached the volcano. The wind, which was light and from the east, carried some tephra in the direction of the ship. The ship, following a predetermined course, was sailing from northwest to southwest of Surtsey and passed under the volcanic cloud about 2 kilometers west of the island. It may be seen from Fig. 9 that as the ship approached the volcano the gradient increased in the positive direction. When the ship came close to, and partly under, the cloud, the gradient suddenly reversed, but as the ship went beyond the volcano, the gradient again became strongly positive. The enhancement of the gradient in the positive direction continued as the ship turned upwind and moved southeast of the crater. The abrupt transients in the recording—two in the negative direction shortly before the reversal and two in the positive direction during the passage under the cloud—may have been caused by lightning, although none was observed.

Later in the day the ship moved downwind of the island, where the volcanic cloud passed overhead. As shown in Fig. 10, the instruments again indicated the presence of negative charge above the ship.

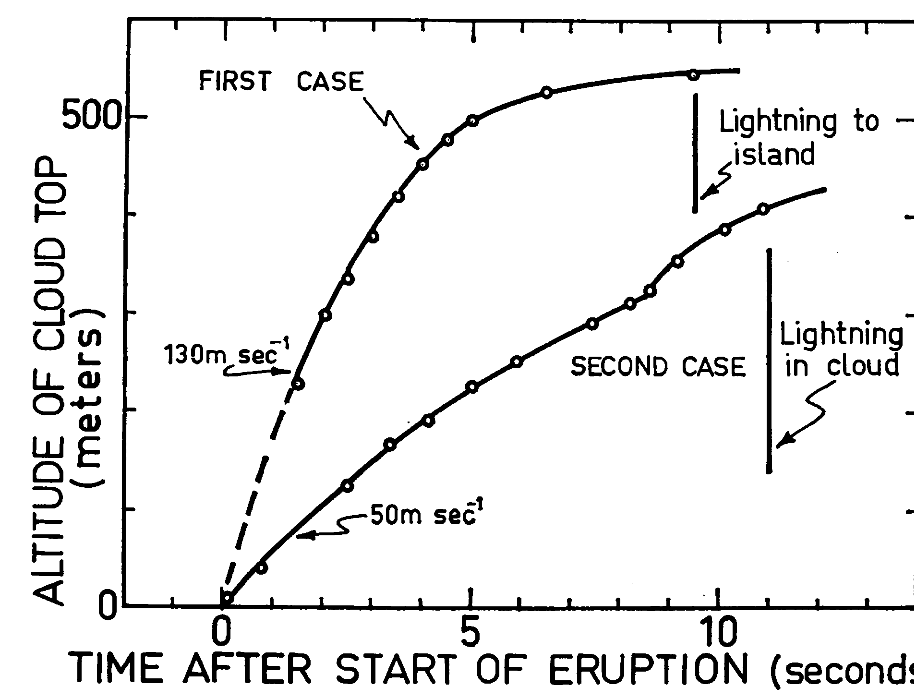

Fig. 7. Height of two black eruption clouds plotted as a function of time after the beginning of the eruption, as determined from motion picture films taken aboard the *Haraldur*.

Observations from Vestmannaeyjar

Both of the groups that sailed on the *Haraldur* in February spent several days on Vestmannaeyjar. In clear weather this location provided a good overall view of the volcanic cloud. Streamers of precipitation were observed falling out of the cloud several kilometers downwind of the volcano, as shown in Fig. 11. From our observations on the *Haraldur* when we passed under the edge of the cloud, we believe this precipitation to have been a mixture of small tephra particles, sea salt particles (*9*), and drops of dirty rain that formed in the volcanic cloud. It appears that this rain was caused by the coalescence of droplets that formed when the superheated steam cooled and condensed. By the time the cloud had moved about 10 kilometers downwind of the volcano, much of the liquid water had usually evaporated, leaving a plume of fine, slowly falling tephra and sea salt particles. These were often reported by aircraft to persist for hundreds of kilometers downwind.

The height of the cloud plume was variable. When the atmosphere was stable, the plume was often trapped in the lower 3 kilometers or so of the atmosphere; at other times, clouds formed by the volcano rose much higher, and on occasion turrets appeared to intrude into the stratosphere briefly before rebounding downward. The altitude of the cloud top shown in Fig. 11 is estimated to be about 6 kilometers.

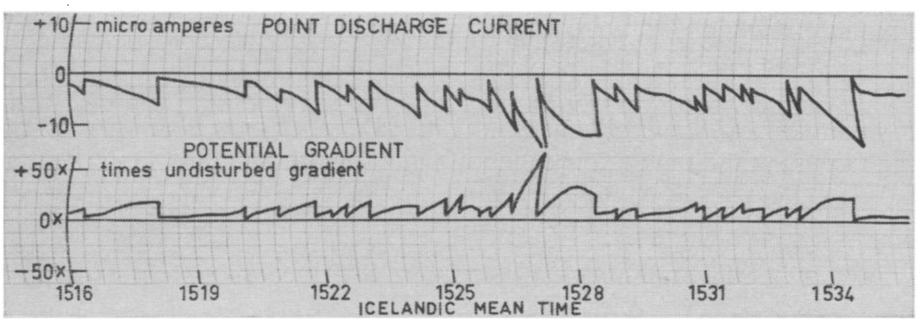

Fig. 8. Strip-chart record obtained aboard the *Haraldur* upwind of the volcano during the most vigorous eruption on 16 February 1964.

When vigorous eruptions occurred, rapidly rising jets and plumes were little affected by the horizontal winds in the atmosphere. Whirlwinds (*7*) frequently formed downwind of these plumes; the vorticity for these probably arose from eddies generated by the wind blowing past the cloud towers.

Almost every night when the visibility was good, lightning could be seen over the volcano from Vestmannaeyjar. On several nights, time-lapse motion pictures of the volcanic activity and lightning were taken with a 16-millimeter camera. The most interesting of these observations was a sequence taken on the night of 4 February during a period when there was a steady, strong west wind and moderate lightning activity. In this series the camera was set up to take open-shutter time exposures at the rate of about 6 per minute from sunset until midnight. The area covered by the camera lens is indicated in Fig. 12 (the active crater of the volcano is in the lower right hand corner of the frame). The orange glow of molten lava in eruptions could often be seen on the film in this region during eruptions.

Because of the concentration of fine,

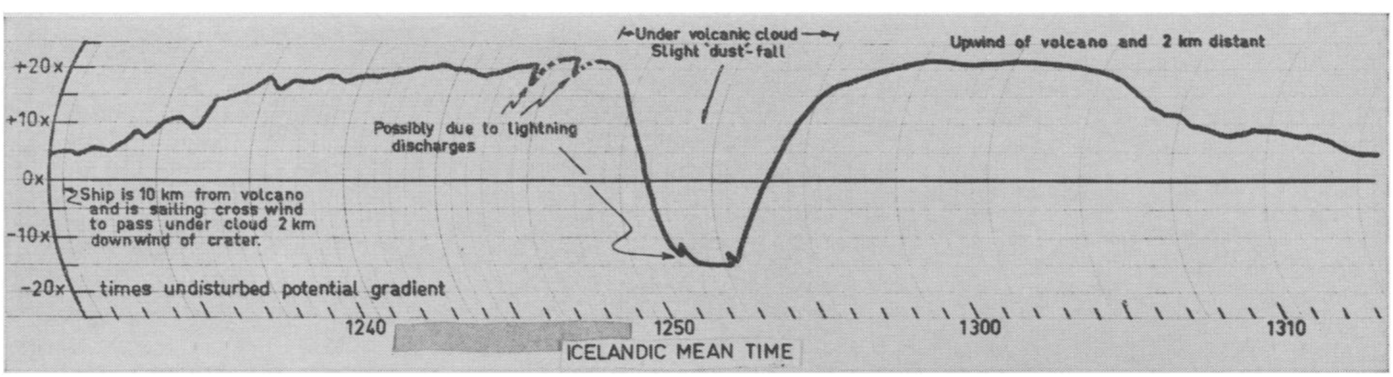

Fig. 9. Potential-gradient recording obtained as the ship passed under the volcano cloud plume 2 km downwind from Surtsey on 22 March 1964.

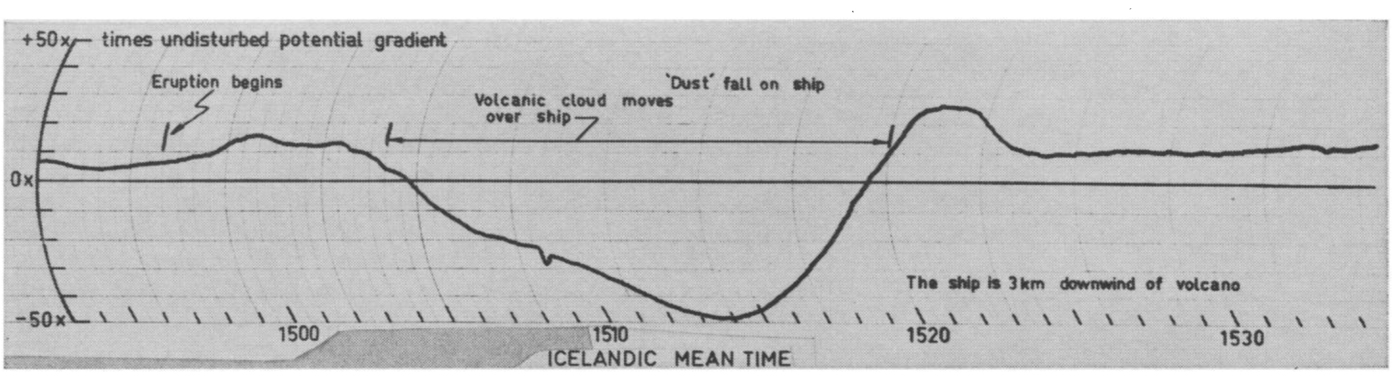

Fig. 10. Potential-gradient recording obtained on the ship 3 km downwind of Surtsey as the volcano cloud passed overhead.

black tephra particles, the volcano cloud was far more opaque than ordinary clouds. For this reason the appearance of lightning over the volcano at night was somewhat different from that in thunderstorms. Discharges inside the cloud did not provide much illumination, and they were entirely screened from view if they occurred at any depth. Undoubtedly there were many undetected strokes, and it is not possible to conclude from these pictures whether the discharges were intracloud or cloud-to-earth. In the photographs, luminous regions resulting from lightning can be readily distinguished from those produced by glowing lava because of their blue or white color.

Quite often the lightning discharges over the volcano appear in the films as one or more bright spots of light on the cloud surface, which may or may not be associated with an exposed spark over another portion of the cloud or a region of diffuse glow. We believe these bright spots are probably short lengths of a lightning spark in the interior of the black volcanic cloud, which can be seen through holes or less dense regions in the cloud, as shown in Fig. 2.

The location of lightning within a thunderstorm cloud is typically variable and unpredictable; by contrast, the visible lightning in the volcano cloud was confined to a rather small volume in the upwind portion of the plume. To obtain an average picture of the distribution of lightning, we made a frame-by-frame examination of the motion picture film. We projected the photographs on a paper surface, and wherever we could see a portion of a lightning spark or detect the presence of one by the diffuse blue luminosity, we made a mark. The resulting composite sketch indicating the distribution of lightning sparks is shown in Fig. 13. Note the number of lightning discharges in the upper part of the picture; when we were watching the volcano we could see that some of this lightning extended above the field of view of the camera, well up into the top of the plume.

We found an average of about 20 discharges per hour. The longest period in which no lightning occurred was about 20 minutes. In several cases lightning can be seen in two alternate frames, but it never appears in successive frames.

From Vestmannaeyjar, short, sharp clicks of radio static were often detected with a small transistor radio tuned to 550 kilocycles. At night it was often possible to correlate these with the appearance of lightning in the cloud over Surtsey.

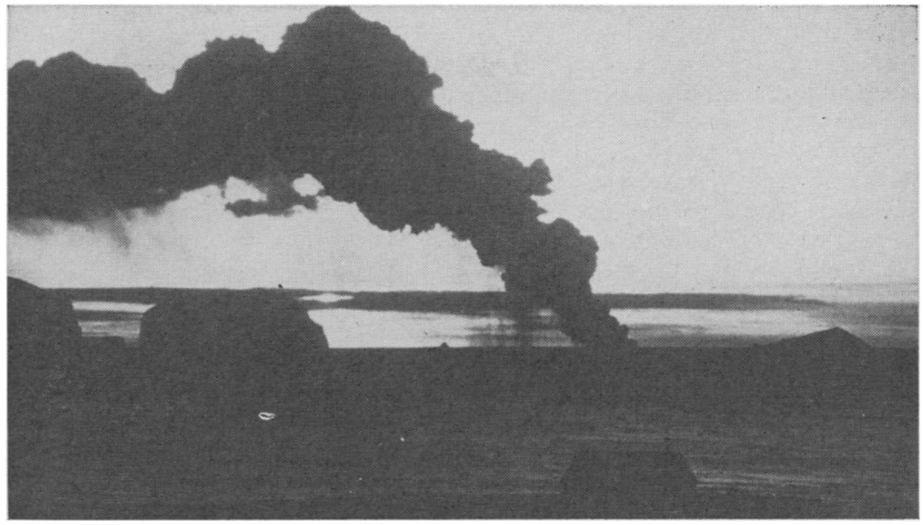

Fig. 11. Typical view of the volcano cloud plume from Vestmannaeyjar, 23 km to the northeast, during December 1963. [Sólarfilma-Reykjavík, Iceland]

Final Surface Observations

Although Surtsey continues to be active, the nature of its activity has changed since the time of our early observations. On 4 April 1964 a wall of scoria formed, preventing sea water from flowing freely into the crater; the violent eruptions and the lightning have ceased since this wall formed. The crater has filled with molten lava, which sometimes flows in streams down into the sea and generates clouds of steam and, presumably, sea salt particles (*9*).

On 24 July, Björnsson, aboard another Icelandic Coast Guard vessel, made measurements of potential gradient under one of these clouds, this time with an adequate probe exposure. On this day a thin stream of hot lava ran into the sea, creating a dense, white plume initially about 10 meters in diameter. The plume was carried by the wind along the shore and out to sea as the cloud rose to about 200

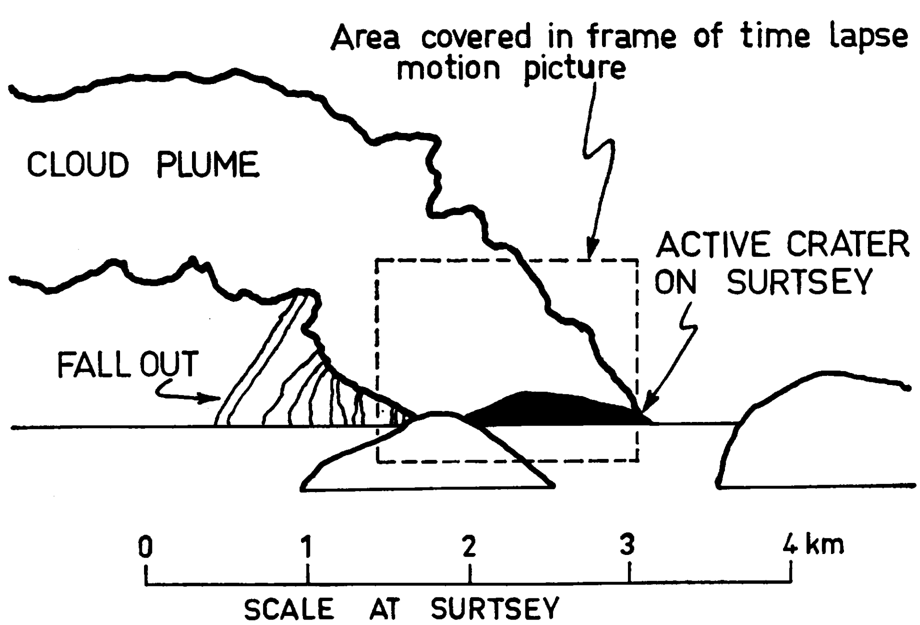

Fig. 12. Outline sketch of the view from Vestmannaeyjar during time-lapse photography of lightning on the night of 4 February 1964.

meters and became a horizontal cylinder about 100 meters in diameter. Its appearance at this time is shown in Fig. 14.

Measurements could not be made at the place where the plume was formed, as it was inaccessible. The ship was able to sail beneath the cylindrical cloud and at right angles to it about 800 meters downwind from its origin and 200 meters offshore. As shown in Fig. 15, a positive potential gradient of about 33 volts per centimeter was observed directly under the cloud. This was about 25 times the value for the fine-weather gradient over the ocean, which was found to be about 1.3 v/cm.

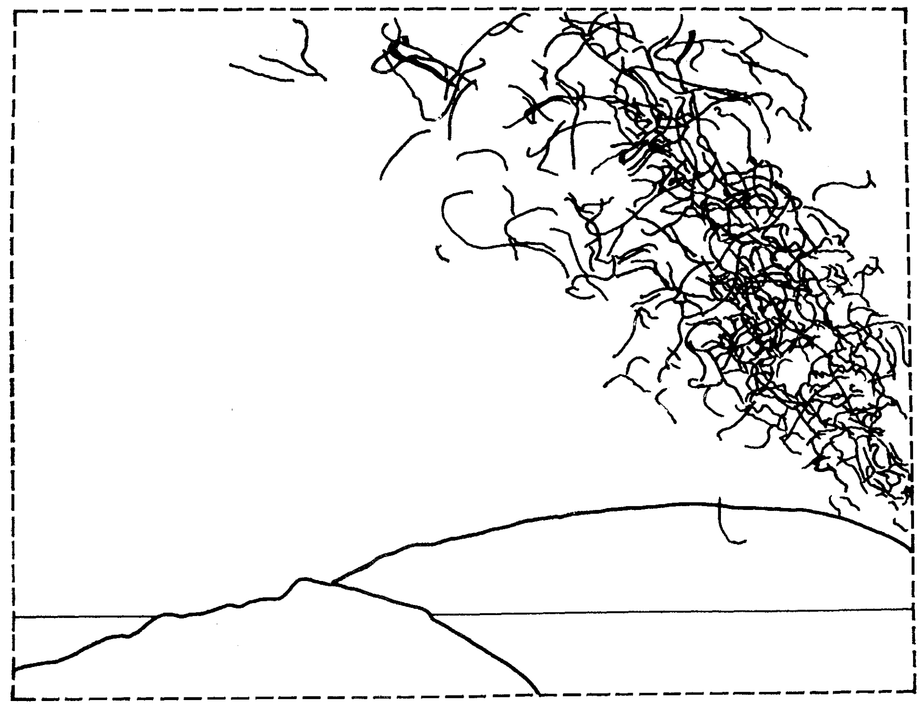

Fig. 13. Composite sketch of lightning in the field of view of camera taking time-lapse motion pictures during the night of 4 February 1964.

Computations of Charge

The frequent lightning over the volcano shows beyond any doubt that quantities of net charge are somehow accumulating in the cloud. We have estimated the magnitude of this charge from our measurements of the electric potential gradient. The results are discussed below.

Estimates from surface observations upwind. Using Björnsson's July value of 1.3 v/cm for the fine-weather potential gradient at the ocean surface, we estimate the potential-gradient aberrations (just before the discharges) produced by the eruptions in February to be about 40 to 80 v/cm at distances of 300 to 500 meters upwind of the volcano. We estimate the magnitude of the positive charge neutralized in the lightning discharges from the relation *(10)* for the potential-gradient change $\Delta(dV/dz)$ produced at the surface of a conducting plane by the neutralization of a point charge Q at an elevation H above the plane and at a slant range of R:

$$Q = 2\pi\epsilon_0 \left(\frac{R^3}{H}\right) \Delta\,(dV/dz)$$

From other measurements of potential gradients beneath thunderstorms over the ocean we believe that charge emission by point discharge from water surfaces plays a negligible role in governing the potential gradient at the surface of the ocean. We tried to take our measurements, when possible, from the upwind side of the vessel to minimize the effects of the appreciable point discharge from the ship itself; however, point discharge from the *Haraldur* may have been responsible for the limitation of the potential gradient observed on 16 February. Accordingly, we have used the sudden changes in the potential gradient for the charge neutralization estimates, as these are likely to be less affected by point discharge.

For much of the lightning that we observed, the top of the cloud was about 500 to 700 meters above the ocean and the tops of the visible discharges were at about 200 to 300 meters. The elevation angle to the top of much of the lightning was estimated to be about 40° to 45°. In these observations the value of the geometric term R^3/H lies between 2×10^5 and 1.3×10^6 m^2, with a mean value of about 5×10^5 m^2.

From these values and the values for the potential-gradient changes that followed the lightning, we estimate that possibly 0.1 to 0.5 coulomb of positive charge was neutralized in many of these discharges. The discharges returned the gradient to about the fine-weather value, so that often the greater part of the charge in the cloud was effectively neutralized by lightning. Since the high potential gradients were often regenerated in 10 to 40 seconds, we infer that charging currents of about 30 milliamperes may have accompanied these eruptions.

We have measured the dimensions of the cloud images on the motion-picture films and have computed the volume enclosed by the cloud edges by assuming the volume to be an ellipsoid of revolution about the vertical axis. At the times of the discharges, two of the cloud outlines enclosed volumes of about 10^8 m^3; from this we estimate net charge concentrations within the cloud of about 2×10^4 elementary charges per cubic centimeter.

The rate of increase of the volume of the volcanic cloud was prodigious: it exceeded 10^7 m^3/sec in several instances. The initial ascent velocity of the steam jets was often about 150 m/sec. From aerial views of the crater we have estimated that the area of the orifice was no larger than 5000 m^2. The volume rate of flow of steam released at 150 m/sec from an orifice of this size is no greater than 10^6 m^3/sec and a small fraction of that estimated from the growth of the cloud outline. We infer from this that the high-speed jets rapidly entrain the surrounding air in forming the volcanic cloud; accordingly, the concentration of the net positive charge in the effluent steam is possibly as much as 100 times the value estimated above.

On the basis of relations discussed by Vonnegut *(11)* we estimate the energy released in one of these discharges to be about 10^6 joules; this is about 1/1000 the energy estimated for a lightning discharge in a thunderstorm.

For the period of active eruptions on 16 February 1964 the estimated average rate of electrical energy release (about 1000 kw) is less than 1/100,000 the estimated rate for thermal energy released from the volcano (7).

Estimates from surface observations downwind. Measurements of potential gradient were made from a Coast Guard cutter on 22 March as it sailed at 6 m/sec under the volcanic plume 2 kilometers downwind from the crater and more or less at right angles to the cloud line. At this time the altitude of the cloud top was 3000 meters above sea level. From the data of Fig. 9 and the value 1.3 v/cm for the fine-weather gradient over the ocean, we estimate that the surface potential gradient was about −20 v/cm when the ship was directly under the plume and zero when it was about 700 meters on either side of the center of the cloud line. Similarly, at a distance of about 2000 meters on either side of the plume the surface gradient was about +30 v/cm.

These observations suggest that a stream of net positive charge above one of net negative charge was associated with the cloud downwind of the volcano. If we assume that the center of "gravity" of the positively charged stream was within the cloud and consider the two streams to be horizontal lines of charge, we can estimate the necessary intensities and separation in altitude. The potential gradient, dV/dz, produced at the surface of a conducting plane by a horizontal, elevated line of charge with a concentration of γ per unit length is $H\gamma/\pi\epsilon_0 R^2$. where H is the altitude of the horizontal line source above the conducting plane and R is the slant range from the point of interest on the conducting plane measured normal to the line. A line with about 1 coulomb of positive charge per kilometer at an altitude of 2500 meters above a line with about 0.7 coulomb of negative charge per kilometer at an altitude of about 1500 meters will produce potential gradients at the ocean surface that closely approximate those observed. Undoubtedly the distribution of charge is more complex than the simple model assumed, because the observed gradients do not decrease quite as rapidly with increasing distance from the cloud as do those in the model. We infer from this that the positive charge in the cloud had a wider horizontal distribution transverse to the plume than did the negative charge.

The vertical depth of the cloud about 2 kilometers downwind from the volcano has been estimated from photographs to be about 1500 meters; the mean charge concentration in a cylindrical cloud with this cross section is estimated to be about 6000 elementary charges per cubic centimeter. The wind was carrying the charged cloud plume horizontally at about 3 m/sec, so the resultant flux of positive charge was about 3 milliamperes.

It is of interest that calculations based on a wide range of assumptions all indicate that the center of "gravity" of the lower charge was within or near the cloud base, and not closer to the ocean surface in the shaft of falling volcanic dust.

The cloud that was produced on 24 July, when the lava flowed from the crater into the sea, carried a net positive charge. From the data obtained we compute that the cylindrical plume of 100-meter diameter carried a charge

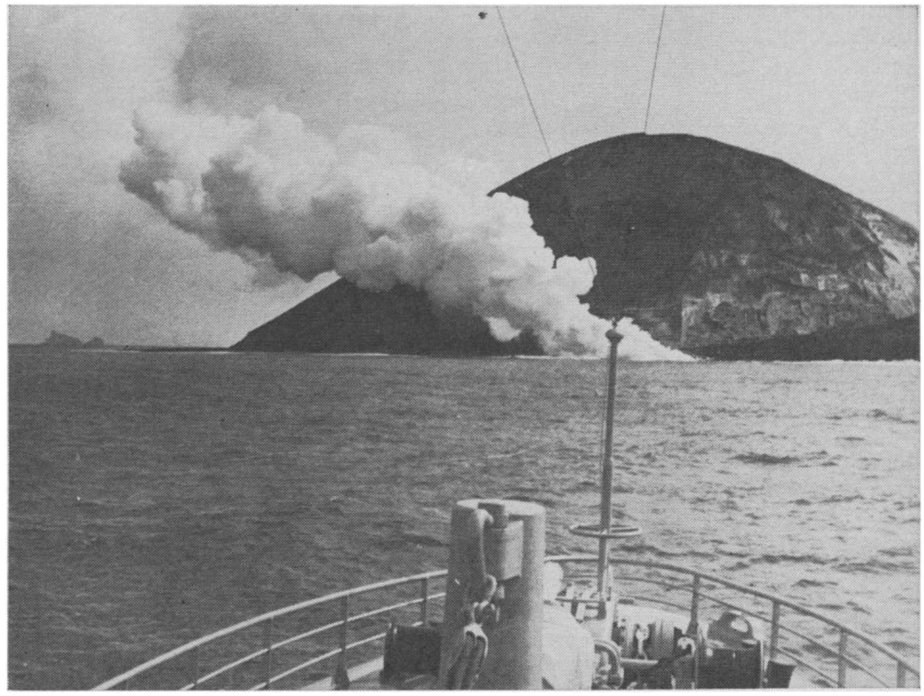

Fig. 14. Charged cloud formed by lava flowing into the ocean, as seen from Coast Guard ship at noon on 24 July 1964.

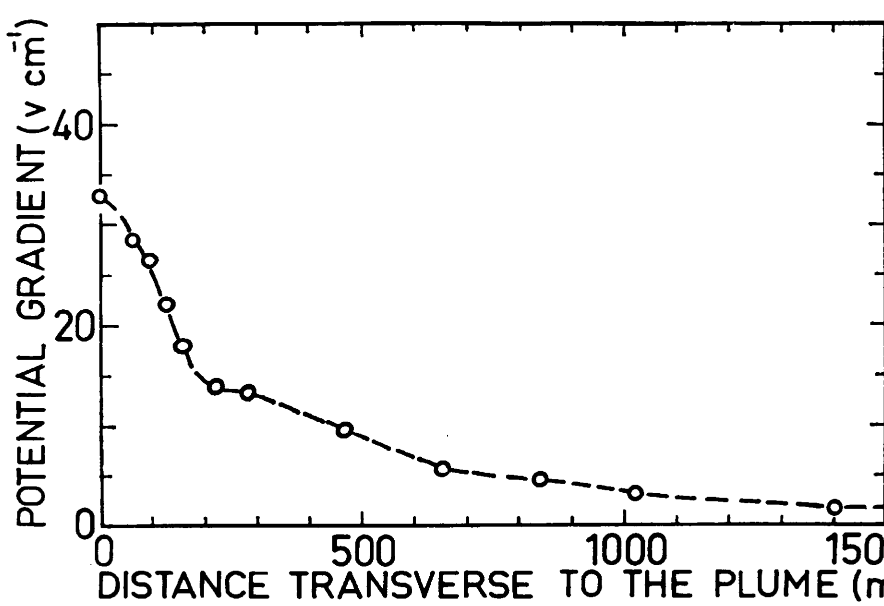

Fig. 15. Transverse distance to the cloud plume plotted versus the potential gradient observed on 24 July 1964 as the ship passed under the charged plume 200 m north of the island and 800 m downwind from the region of contact between lava and ocean.

of about 0.01 coulomb/km, and therefore carried a net charge concentration of about 10^4 positive elementary charges per cubic centimeter. This value is essentially the same as that estimated for the cloud of Björnsson's observation of 22 March. As the diameter of the plume was about 10 meters at its source, the charge concentration in the cloud at that point must have been about 10^6 elementary charges per cubic centimeter.

Estimates from airplane observations downwind. In view of Björnsson's surface observations of 22 March which indicate clearly the presence of negative charge in the lower portion of the cloud downwind, it is not possible to estimate the charge concentration from measurements made from the airplane. The maximum field excursions observed from the plane could have been produced by charges of the magnitude calculated from Björnsson's observations, so the aerial and surface observations immediately downwind are approximately compatible although they were obtained at different times.

Of considerable interest is the trend of the electric field observed on 16 February as the plane followed a charged cloud downwind. The electric field around the cloud was greatest near the crater; it decreased by an order of magnitude within 10 minutes after the eruption, and thereafter relaxed with a time constant of about 7 minutes. Charge decay by atmospheric conduction therefore can be an explanation for this relaxation. At no time after the eruption were there any increases in the electric field that suggested charge generation as tephra and rain fell from the cloud downwind. Relaxation of the gradient at a similar rate was observed from the Coast Guard ship as it followed the plume downwind on 24 July.

Discussion

The thermal energy supplied to the atmosphere by Surtsey is comparable to that supplied by a thunderstorm. From Braham's data (*12*) it can be estimated that in an average thunderstorm the rate of energy release from the heat of the condensing water is of the order of 3×10^{18} erg/sec. Thorarinsson and Vonnegut (*7*) have estimated that thermal energy was released by the eruption at Surtsey at approximately 10^{18} erg/sec. It is evident that when the atmosphere is thermally unstable the heat input from the volcano could initiate strong convective activity approaching thunderstorm proportions. It seems probable that, under these conditions, the electrification mechanisms of thunderstorms would act in addition to the electrification produced by the volcano. However, the atmosphere was quite stable thermally during all of our measurements in February and March of 1964, and there was no thermal convection suggestive of a thunderstorm. We therefore doubt that thunderstorm electrification processes were a factor during the periods of our observations. Thunderstorm electrification may, of course, have contributed to some of the more intense electrical displays, such as that observed on 1 December 1963 and shown on the cover and in Fig. 2.

The volcano-cloud electrification observed in February and March of 1964 was associated with high-velocity eruptions of gas-borne tephra. The following features of our observations lead us to conclude that the matter ejected during these eruptions was highly electrified, with positive charge, as it issued from the crater.

1) The potential gradient rapidly intensified during the vigorous black eruptions. Lightning was observed only during the high-velocity emission of tephra.

2) The visual and photographic observations in February showed that lightning occurred shortly after the start of vigorous eruptions and that the discharges were confined to the youngest part of the cloud, near the crater. The time interval between the start of an eruption and the discharge of lightning from each new cloud was so short that it is difficult to explain the accumulation of the necessary charge in terms of a charge separation process that took place in the atmosphere after the cloud had been formed.

3) Measurements from the ocean surface and from the air show that the potential gradient was most intense near the crater and that it rapidly diminished with distance. These measurements also indicate that over the crater the cloud was charged positively and had no detectable dipole structure.

4) Near the crater, the changes in the potential gradient which were produced by lightning invariably indicated that, in the discharges, positive charge aloft was neutralized or lowered toward the earth. Our measurements of the potential gradient upwind of the volcano showed no evidence of negative charge in the cloud over the island.

Our electrical observations upwind of Surtsey are similar to those made near volcanic eruptions in Japan by Hatakeyama and Uchikawa (*4*), by Ishikawa *et al.* (*5*), and by Hatakeyama (*2*). Their data also show that the greatest electrical disturbances are produced by vigorous black eruptions and that near the volcanic crater the charge in the cloud is predominantly positive.

The subterranean electrification process responsible for the positive charge in the high-velocity tephra eruptions may be similar to that which Blanchard (*13*) has demonstrated in the laboratory and that which we found to be taking place when molten lava overflowed into the ocean. Blanchard found that the contact of sea water with molten lava resulted in the production of a positively charged cloud of particles; Woodcock and Spencer have shown that these particles are composed of sea salt (*9*). The charge concentration in these laboratory-created clouds was estimated to be at least as high as 10^6 elementary charges per cubic centimeter. As this is the order of magnitude of the charge concentration which we estimate to be carried by the cloud as it emerged from the crater of Surtsey, it is tempting to attribute the positive electricity in the Surtsey cloud to the contact of sea water with magma in the crater. However, caution must be used here, for the conditions during the eruption are exceedingly complex, and other charge-separation mechanisms undoubtedly played a role. For example, electrification must also occur when particles carried in the erupting gases collide with the walls of the crater throat.

Since land volcanoes, such as the presently active Irazú in Costa Rica (*14*), are also electrified even though sea water is not present, studies of their charge emissions may shed some light on the relative importance of the various electrification processes.

Our observations downwind of Surtsey are similar to those that have been made in Japan by Ishikawa *et al.* (*5*) and by Hatakeyama (*2*), for they show that the electrified cloud is bipolar and that, downwind, there is a region of negative charge beneath the region of positive charge.

Two mechanisms have been proposed to explain the origin of the negative charge downwind of the volcano. The first, suggested by Ishikawa *et al.* (*5*), is that the negative charge arises from a process of induction caused by the positive charge. The second, suggested by Hatakeyama (*2*), is that the negatively charged region accumulates as the result of the falling of charged tephra particles that have selectively acquired negative charge by collision.

Our measurements show that in the strong, positive potential gradients near the volcano, negative ions were flowing into the atmosphere by point discharge from the *Haraldur*. Unquestionably a much larger point discharge current of negative charge was also flowing into the air from the volcanic island; this charge was carried downwind along with the positively charged cloud, probably becoming attached to cloud and tephra particles.

On the other hand, a light fall of tephra was associated with the negative-gradient maxima observed downwind of the volcano. From our data no determination can be made as to whether this association was merely the result of Björnsson's being directly under the cloud dipole from which tephra was falling or whether there was a cause-and-effect relation between the falling tephra and the negative charge; we were not able to measure the charge carried by the falling tephra as Hatakeyama did (*2*). One of the problems to be solved before we can understand the atmospheric electrification caused by volcanoes is that of establishing the relative importance of these two possible sources of negative charge.

Our observations of Surtsey on 24 July must be considered separately from the others, for they show that significant charge was associated with a cloud that had no connection with high-velocity eruptions, tephra, or subterranean processes. The charged cloud was formed when molten lava flowed from the island and made contact with the sea. It is highly probable that the process of cloud formation is the same as that studied by Woodcock and Spencer (*9*), and that the charge separation is the result of the contact of sea water with molten lava (see *13*). The mechanisms of particle formation and electrification are far from clear.

Summary

In November of 1963 an oceanic volcano produced an island, Surtsey, just off the southern coast of Iceland. The volcanic crater was often flooded with sea water. Vigorous eruptions of steam and tephra were accompanied by an enhancement of the normal fine-weather potential gradient, and lightning was often observed. Measurements of atmospheric electricity and visual and photographic observations lead us to believe that the electrical activity is caused by the ejection from the volcano into the atmosphere of material carrying a large positive charge. The concentration of charge in the eruption plume as it issued from the orifice of the volcano is estimated to be of the order of 10^5 or 10^6 elementary charges per cubic centimeter.

In April of 1964 the crater was closed off from the sea. It filled with molten lava, and occasionally a lava stream would flow down into the sea. Upon contact with the sea water the molten lava produced a dense, white, positively electrified cloud. The initial charge concentration in this cloud was of the order of 10^6 elementary charges per cubic centimeter.

It may be that the positive charge arising from the zone of lava-sea contact and that arising in the violent eruptions of tephra are produced by a process similar to that observed by Blanchard (*13*) in his laboratory.

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