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Electrical activity during the 2006 Mt. Augustine volcanic eruptions

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It has long been known that volcanic eruptions can produce vigorous lightning. Early investigations of volcanic lightning were made during the Surtsey and Heimay eruptions in Iceland in 1963 and 1973 (*1,2*). Despite increasing interest (*3,4,5*), volcanic lightning continues to be poorly understood as there are few direct scientific observations of the phenomena. We report observations of lightning during the recent eruptions of Mt. Augustine in Alaska that provide a more detailed picture of volcanic lightning than heretofore available.

Following the initial eruptions of Mt. Augustine on January 11 and 13, 2006, two of which produced lightning, we deployed two time-of-arrival mapping stations on the east coast of Cook Inlet 100 km east of Augustine (Fig. S1). The stations constituted a minimal network capable of determining the azimuthal direction of impulsive radio emissions from electrical discharges (*6*).

Within two days of the stations being set up Augustine erupted again, producing four explosive eruptions during the night of January 27–28, 2006 (*7*). Although not observed visually due to stormy weather, the data showed that the first and largest of the eruptions produced a spectacular lightning sequence (Fig. 1). Seismic data indicate that the eruption lasted about 11 minutes, from 05:24 to 05:35 UTC, with a particularly energetic explosion occurring between 05:31 and 05:33.

The main explosion, and a smaller explosion ∼3 min earlier, were accompanied by continuous backgrounds of strong, impulsive radiation events and by several embedded lightning-like bursts (Fig. 1A). The bursts were detected by both measurement stations and originated from the direction of Augustine's summit (Fig. 1B). The background radiation, although strong, was not detected at the northern station and is believed to have originated at low altitude immediately above or within Augustine's vent. Its presence is indicative of a myriad of small discharges within the superheated ejecta as it exited the volcano.

The main explosion was followed after a delay of ∼3 min by a sequence of about 300 well-defined lightning discharges between 05:34:11 and 05:45:31 UTC. The discharges drifted southward from Augustine's summit (Fig. 1B), in the same direction as the Nexrad-detected radar plume. One of the final discharges lasted 650 ms and had a transverse extent of 15 km, extending to 22 km away from the volcano (Fig. 1C). These discharges undoubtedly occurred within the volcano's plume, which developed up to 8–10 km altitude.

Although not planned, the southern station fortuitously functioned as a 'sea-surface interferometer', in which direct and water-reflected signals interfered constructively or destructively at the receiving antenna depending on the height of the radiation source above the volcano. The interference effects were clear for a radiation burst at 05:32:14 during the main explosion. Together with the azimuthal data, the results show that the burst was produced by an upward-initiated, ~4-km long discharge from Augustine's summit that developed horizontally into the downwind plume (Fig. 1D). The radiation was characteristic of negative-polarity breakdown into net positive charge in the plume (*S4, 8*). Some discharges of the delayed lightning sequence may have been initiated upward from the summit, but most were undoubtedly intracloud discharges (*S5*).

Overall, the observations of the January 27–28 eruptions indicate that Augustine's electrical activity had two modes or phases. First, a newly-identified explosive phase in which the ejecta from the explosion appeared to be highly charged upon exiting the volcano, resulting in numerous apparently disorganized discharges and some simple lightning (Fig. 1D). The net charge exiting the volcano appears to have been positive – the same polarity observed for the Icelandic volcanoes involving direct contact with sea water (*1,2*). In the second phase, conventional lightning discharges occurred within the plume cloud produced by the explosion. While the plume was undoubtedly charged as a result of the explosion, the fact that the plume lightning was delayed and continued after and well downwind of the eruption indicates that in-situ charging also occurred within the plume, for example as a result of particle interactions involving tephra, ash, and ice hydrometeors. Volcanoes are known to release copious amounts of water and may behave as 'dirty thunderstorms' (*9*).

References and Notes

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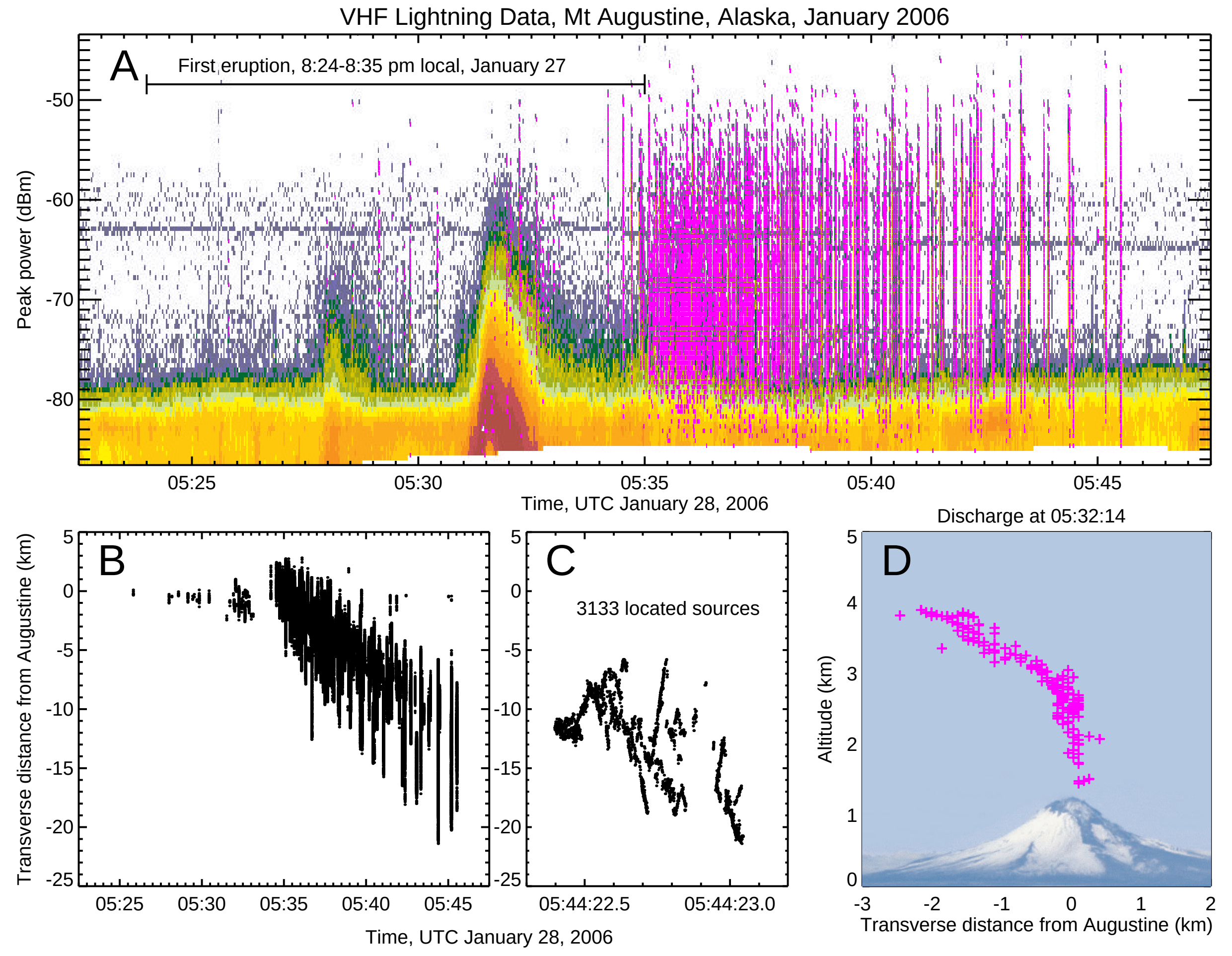

Fig 1: Overview of the electrical activity during the initial eruption on January 27. (A) Peak radiated power values at the southern station, with azimuthally located events shown in magenta. (B) Transverse distance of the located discharges relative to Augustine. (C) Temporal development of a final lightning discharge near the end of the activity. (D) Vertical projection of an upward discharge during the main explosion.

Supporting Online Material

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Materials and Methods

The initial deployment of measurement stations consisted of two instruments positioned on the east coast of Cook Inlet (Fig. S1). The southern station was at the Alaska Volcano Observatory field station north of Homer, AK, and the northern station was at the Anchor Point Public Library, 17.1 km NNW of the Homer site. The receiving antenna at the Homer station was located on the edge of a high (220 m) bluff overlooking Cook Inlet, with direct line of sight to Augustine. The Anchor Point station was located at 125 m altitude about one mile inland from the coast and did not have a direct view of Augustine.

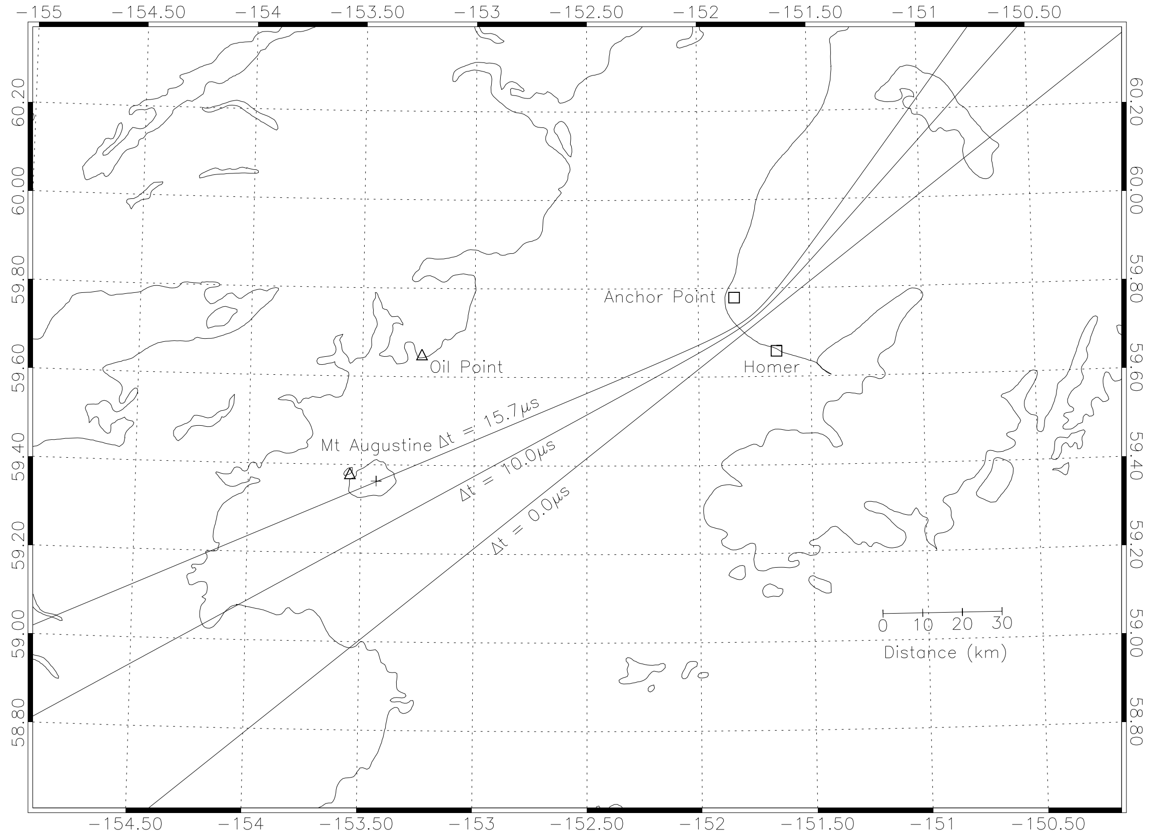

Fig S1: Map of the area showing Mt. Augustine and the location of the initial two lightning mapping stations (squares), and two remote stations added after Feb. 13 (triangles). The three hyperbolae show the directions of arrival corresponding to 0, 10, and 15.7 μs time differences.

Each station accurately measured the arrival times of impulsive radiation events in a locally unused VHF television channel (Channel 3, 60–66 MHz). Arrival times were measured with 40 ns time resolution for the peak radiation events in successive 80 μs time intervals (*S1*). An arrival time difference of 15.7 μs corresponded to signals coming from the direction of Augustine's summit;

signals originating in a southward direction from Augustine had decreased time differences as indicated in Fig. S1. The temporal quantization corresponded to about 75 m azimuthal resolution at the 106 km distance of Augustine.

In addition to measuring arrival times, the stations also recorded the peak power of each radiation event. Because it was somewhat inland and in a noisier radio frequency environment, the Anchor Point station was less sensitive to signals from Augustine than the Homer station. While Anchor Point functioned well for higher-altitude events, it did not detect the noisy radiation during the explosive phases, even though the Homer data showed this radiation to be as strong or stronger than that of more organized discharges (Fig. 1A). This indicates that the explosive-phase radiation originated at relatively low altitude at or slightly above Augustine's summit, where the signals would have been more strongly attenuated at Anchor Point. The radiated source powers ranged from about 0 dBW up to 30 dBW (1 to 1000 W) in the receiver passband, typical of the values observed for ordinary lightning (*S2*).

Fig. S2 illustrates how the Homer station functioned as a sea interferometer (*S3*). The relatively simple discharge of Fig. 1D produced received power values versus time which showed clear evidence of interference fringes (Fig. S3C). To remove the effect of variations in the source power itself, the Homer power values were referenced to those of the same events at Anchor Point, which did not experience interference effects.

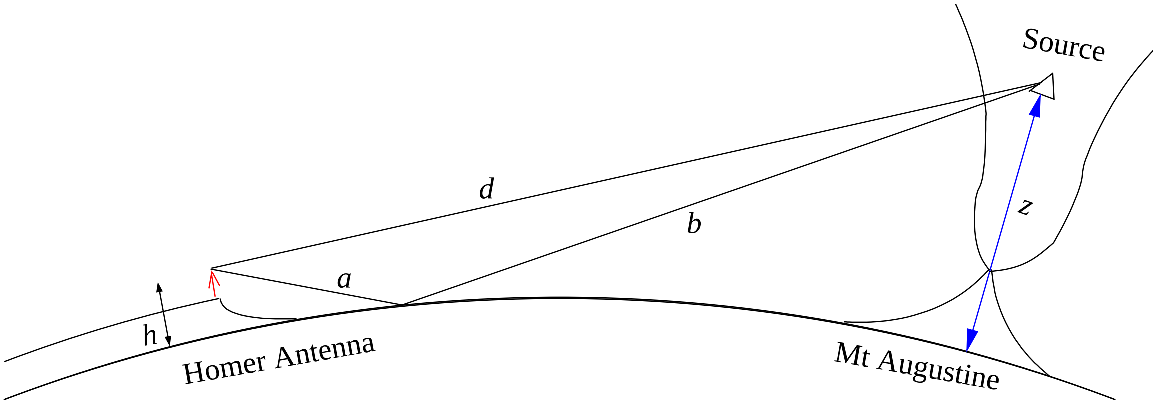

Fig S2: Diagrammatic illustration of the sea surface interferometer. The radio waves reach the receiving antenna by a direct path (d) and a reflected path (b, a).
The curvature and height scales are greatly exaggerated in the illustration; the distance d is 100 km, $h = 220m$ and z ranges from 1.3 km to 8 or 10 km.

The predicted interference pattern is shown in Fig. S3D along with the results of fitting the measurements to the predicted pattern. To obtain the predicted pattern it was necessary to take into account the curvature of the earth as well as the fact that sea water is a reasonably good conductor, with a phase shift close to $-\pi$ upon reflection. Because of the extreme grazing nature of the reflections (the incidence angle varied between $\sim$0.5 and 2.0° from horizontal for the discharge of Fig. 1D), the path length difference for the direct and reflected signals was only about 0.6λ for signals originating at Augustine's summit (1260 m altitude) and increased at a rate of about 0.9λ per kilometer above Augustine. Thus, in going $\sim$2 km upward, the discharge at 05:32:14 exhibited two complete interference fringes (Fig. S3D).

Several steps were taken to fit the observational data to the predicted values. First, the logarithmic power differences needed to be shifted downward by 15 dB to compensate for the attenuation of the Anchor Point signals. Second, to match the depth of the interference minima, the reflection coefficient of the sea surface was adjusted to an effective value of 0.7 (versus 1.0 for an ideally smooth conducting surface). Finally, a piecewise-linear approach was used to map temporal intervals in the observed data to spatial intervals on the predicted interference fringes (Figs. S3A, C). To accomplish this, a particular set of points in the temporal data were assumed to originate at heights that gave reasonable 'eyeball' fits between the observed and predicted power values. The resulting time-height conversion (Fig. S3B) was then used to convert the transverse distance vs. time data of Fig. S3A to a 2-dimensional vertical projection plot.

Fig. S4 shows the resulting vertical projection. The discharge appeared to begin about 250 m above Augustine's summit and progressed upward and leftward along a single, 4-km long path. The average speed of progression was about 0.7×10^5 m sec^{-1} vertically and about 1×10^5 m sec^{-1} overall in the transverse plane. Such propagation speeds are characteristic of negative polarity breakdown propagating toward or through net positive charge (*S4*).

The starting point of the upward discharge in Fig. S4 is only an apparent location that corresponded to the time that the sources started being detected by the Anchor Point station. The single-station power data from Homer show clear evidence of propagating breakdown prior to being detected at Anchor Point, indicating that the discharge began at lower altitude, almost certainly on the ground in the vicinity of the summit (*S5*). Because the choice of the initial fringe is ambiguous, we cannot strictly rule out the possibility that the discharge began an integer number of fringes higher in altitude. But this is considered unlikely in view of the above physical interpretation of the observations. There is also an ambiguity as to whether the discharge developed downward or upward, but this is readily resolved from the fact that downward development would give a physically incorrect picture of the discharge relative to the plume.

Because of the possibility of additional eruptions, during the week of February 13–20 two additional stations were deployed at remote uninhabited sites closer to Augustine on the west side of Cook Inlet (Fig. S1). One station was placed on the West Island of Augustine itself, 7 km west of the summit, while the second station was placed on the mainland high above Oil Point (520 m above Cook Inlet), 34 km north of Augustine. The stations operated automatically and unattended on battery power for a period of 1 to 1.5 months but recorded only a small amount of data, primarily because the volcano went into a dome-building phase, with substantially decreased explosive activity.

References and Notes

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S4. Lightning emits radio frequency radiation primarily from developing negative-polarity breakdown, which propagates into positive charge regions, rather than from positive breakdown, which propagates into negative charge regions. The upward radiation sources of Fig. 1D are identical in character to the initial breakdown of intracloud discharges in thunderstorms,

which is of negative polarity and propagates into and through regions of net positive charge (e.g., S7). The propagating radiation segments seen in Fig. 1C are also produced by negative breakdown through positive charge regions.

S5. No cloud-to-ground discharges were detected by the Bureau of Land Management's Alaska Lightning Detection System during the Jan 27-28 eruption. Upward-initiated discharges from the ground would not be detected by the Alaska system because such networks locate the strong 'sferic' produced by return strokes initiated by downward leader breakdown. The Alaska network detected cloud-to-ground discharges only during the Jan 13 eruption – two that lowered positive charge to ground during the initial eruption, and one that lowered negative charge to ground during a later eruption.

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S7. We acknowledge important contributions by Nicholas O'Connor and Sandra Kieft in preparing for and conducting the field studies. This work was supported by the U.S. National Science Foundation under Grant ATM-0536950 and ATM-0354218. Partial support was also provided by the Alaska Volcano Observatory, the U.S. Geological Survey, the State of Alaska, and NSF Grant ATM-0538319.

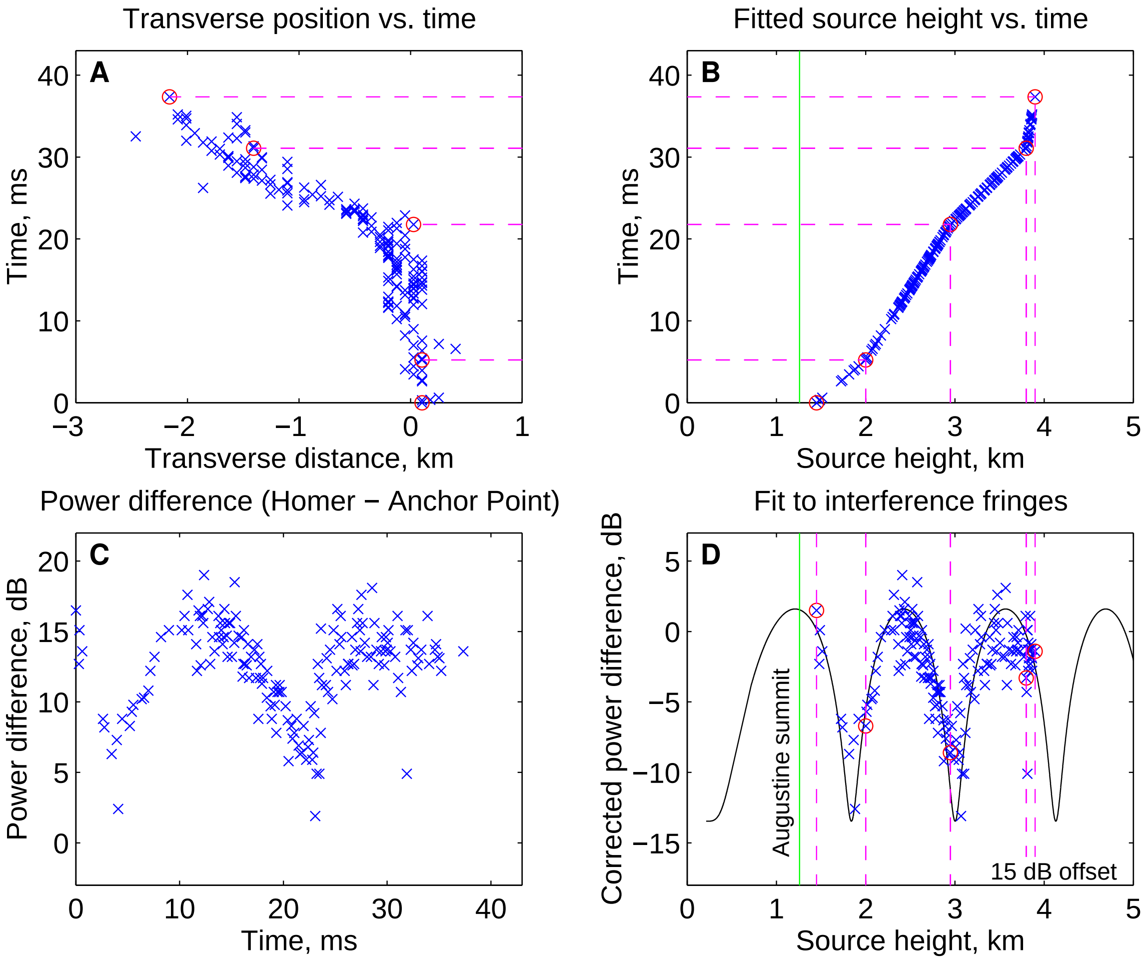

Fig S3: Determining source height vs. time from the basic observational data for the discharge at 05:32:14. The transverse location values (A) were determined from the arrival time differences at the two stations. The received power values at the Homer station (C) are referenced to those at Anchor Point by differencing their logarithmic values, which clearly reveals the interference fringes. The set of circled points and dashed lines indicate the times at which altitude values were chosen that fit the temporal power differences to the predicted spatial fringe pattern in a piecewise linear manner (B, D). The discharge was assumed to have been detected at both stations in the first fringe a short distance above the summit (vertical line)(see text).

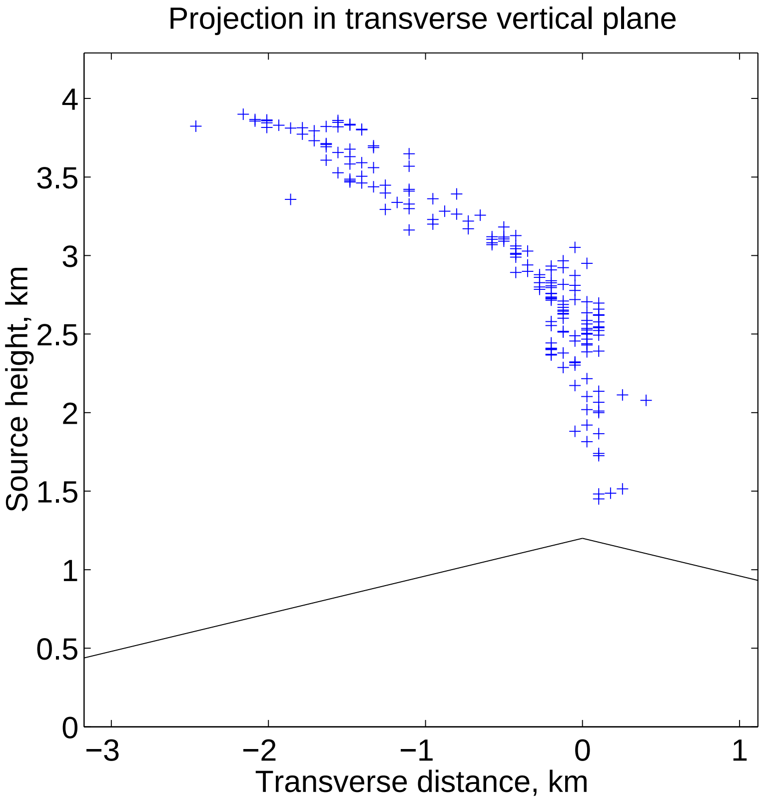

Fig S4: Projection of the upward discharge at 05:32:14 onto the vertical transverse plane, relative to Augustine's summit.