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The evolution of volcanic plume morphology from short-lived eruptions

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Corresponding Author:	Kirsten Chojnicki, Ph.D. Scripps Institution of Oceanography La Jolla, CA UNITED STATES
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Scripps Institution of Oceanography
Corresponding Author's Secondary Institution:	
First Author:	Kirsten Chojnicki, Ph.D.
First Author Secondary Information:	
Order of Authors:	Kirsten Chojnicki, Ph.D.
	Amanda B. Clarke
	Jeremy C. Phillips
	Ronald J. Adrian
Order of Authors Secondary Information:	
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Suggested Reviewers:	Jeffrey Johnson JeffreyBJohnson@boisestate.edu Experience in analyzing volcanic plume images.
	Gregory Waite gpwaite@mtu.edu Experience analyzing volcanic plume and geophysical observations of volcanic eruptions.
	Jacopo Taddeucci

	jacopo.taddeucci@ingv.it Experience imaging volcanic plumes and eruptions and interpreting their dynamics.

The evolution of volcanic plume morphology from short-lived eruptions

K. N. Chojnicki[1], A. B. Clarke[2], J.C. Phillips[3], R. J. Adrian[2]

[1]Scripps Institute of Oceanography, [2]Arizona State University, [3]University of Bristol

Abstract

The details of volcanic plume source conditions or internal structure cannot readily be revealed by simple visual images or other existing remote imaging techniques. For example, one predominant observable quantity, the spreading rate, in steady or quasi-steady volcanic plumes is independent of source buoyancy flux. However, observable morphological features of short-duration unsteady plumes appear to be strongly controlled by volcanic source conditions, as inferred from recent work in Chojnicki et al. [2015]. Here we present a new technique for using simple morphological evolution to extract the temporal evolution of source conditions of short-lived unsteady eruptions. In particular, using examples from Stromboli and Santiaguito volcanoes, we illustrate simple morphologic indicators of a) increasing source injection during the early phase of an eruption; b) onset of source injection decline; and c) the timing of source injection cessation. Combined, these indicators allow estimation of changes in eruption discharge rate, injection duration, and may assist in estimating total mass erupted for a given event. In addition, we show how morphology may provide clues about the vertical mass distribution in these plumes, which could be important for predicting ash dispersal patterns.

1. Introduction

Three classes of volcanic plumes can be differentiated by the relationship between two time scales, the eruption duration and rise time [e.g., *Sparks et al*., 1997]. The eruption duration is the time over which material is injected into the plume. The rise time is the time over which the plume reaches its maximum height. Plumes with short rise times relative to long eruption (injection) durations are classified as sustained or steady columns. Plumes with long rise times relative to the nearly instantaneous duration of explosions are classified as thermals. The third class of plumes is intermediate to the first two and is characterized by plume rise times that are comparable to short eruption durations. Plumes in this class are short-lived and highly unsteady. Each class exhibits a distinct relationship between the eruption (or injection) conditions and the plume rise dynamics that control plume morphology.

Sustained volcanic columns tend to have conical geometries [e.g., *Wilson*, 1976; *Sparks et al*., 1997], and volcanic thermals tend to have approximately spherical geometries [e.g., *Wilson*, 1976; *Sparks et al*., 1997]. Both of these geometries are thought to indicate that the plume is in a self-similar dynamic state (i.e., the flow morphology does not change in time), and that the flow can be described reasonably well with analytical models that approximate the detailed turbulent dynamics [*Morton et al*., 1956]. According to these models, the rise of sustained volcanic columns is primarily controlled by the rate at which buoyant fluid is discharged into the plume; on the other hand, thermals are controlled by the total amount of buoyant discharged fluid, not the discharge rate [e.g., *Morton et al*., 1956; *Wilson*, 1976; *Sparks et al*., 1997].

Intermediate volcanic plumes take on a variety of morphologies [e.g., *Patrick*, 2007]. These include features that are spherical and conical, as well as cylindrical [*Patrick*, 2007].

These morphologic characteristics also evolve over time, changing throughout the plume rise process [e.g., *Patrick*, 2007; *Mori and Burton*, 2009; *Chojnicki et al*., 2015]. The morphologies are not well understood and lack analytical descriptions, but here we seek a method of inferring the dynamic flow conditions in these intermediate plumes and the factors that control them using observations of their morphological evolution.

The initial rise of volcanic plumes before they reach their maximum height and form a conical column has been modeled as a 'starting plume' [*Turner*, 1962 *Wilson and Self*, 1980; *Sparks and Wilson*, 1982; *Patrick*, 2007]. According to this description, the starting plume has two prominent features, a spherical head and a conical tail. The dynamics are different in each feature. The spherical head contains a starting vortex structure and the conical tail contains a steady jet structure [*Turner*, 1969]. While this model appears to capture some aspects of intermediate volcanic plume morphology, such as the presence of spherical heads [*Chojnicki et al*., 2015], it cannot explain the cylindrical geometry of some plumes such as those identified by Patrick [2007].

Kitamura and Sumita [2011] attribute these cylindrical features to unsteadiness in discharge conditions after finding they could not reproduce the cylindrical features in analogue laboratory jets evolving from a steady rate of buoyant discharge. Our previous laboratory experiments support this claim, as we were able to generate neutrally buoyant analogue jets with cylindrical geometries using an unsteady discharge rate [*Chojnicki et al*., 2015]. We observed the evolution of both the analogue jet morphology and the internal velocity fields and found that the analogue jet morphology is a good indicator of the jet internal velocity structure and dynamics. Furthermore, and most importantly, we found that changes in the analogue jet morphology correlate well with changes in the discharge rate. We therefore apply our laboratory analysis to observations of volcanic plumes to show how morphology may be used as an indicator of discharge conditions for intermediate plumes. Because ground-based observations of volcanic plumes from short eruptions (tens to hundreds of seconds) are becoming increasingly common [*Patrick*, 2007; *Mori and Burton*, 2009; *Lopez et al*., 2013; *Valade et al*., 2014; *Webb et al*., 2014], we anticipate that this approach will be applicable in a wide range of field settings in the future.

2. Analogue Jet Experiments

The analogue jet experiments used here are discussed in detail by Chojnicki et al. [2014, 2015]. We provide a brief summary here. Our experiments were performed under idealized conditions in the laboratory so that both the jet and the source could be measured simultaneously. Turbulent jets were generated in the laboratory by injecting water at high-speeds into a tank of still water through a circular vent. The injection durations were comparable to, but shorter than, plume rise times, consistent with conditions for intermediate eruption plumes [*Clarke et al*., 2009]. The experimental injection rates varied in a Gaussian-like temporal evolution, consistent with conditions for short-lived eruptions [*Clarke et al*., 2002], with a total duration of 0.40 seconds. We measured the resultant jet morphology as well as the structure of the internal flow field using Particle Image Velocimetry [*Chojnicki et al*., 2015; following *Adrian*, 1984]. The analogue jets were seeded with silver-coated particles and illuminated by a laser light sheet, producing the unprocessed PIV images presented in Chojnicki et al. [2015]. The tank water appears black relative to the seeded jet water, creating a visualization similar to a dyed jet [Panel a in Figures 1, 2, and 3]. We deem these images to be the best way to simultaneously visualize jet morphology and the fluid velocity field.

The analogue jets created by the Gaussian-form injection rates evolved in three phases [*Chojnicki et al*., 2015]. The vent condition during Phase 1 is characterized by an increase in the injection rate over time. During Phase 1 the jet forms two main regions - a spherical head and a roughly cylindrical tail (Figure 1a). The spherical head consists of a starting vortex structure (labeled V1), common in jets moving into still ambient fluids [e.g., *Kieffer and Sturtevant*, 1984]. The cross-sectional width of the head is larger than the cross-sectional width of the tail. The tail has two sections, labeled 2 and 3, with cross-sectional widths similar to the starting vortex (section 2) and the vent (section 3).

The vent condition of Phase 2 is characterized by a decrease in the injection rate over time. The arrival of Phase 2 is indicated by the appearance of a narrow ‘neck’ region between the starting vortex and section 2 of the cylindrical tail (Figure 2a), which develops as the starting vortex pulls away from the more slowly injected tail. The propagation of Section 2 slows as it moves away from source while section 3 continues at the same velocity due to inertia; the two sections thus start to combine into a conical form in Phase 2.

After injection ends, the analogue jet enters Phase 3 (Figure 3a). The arrival of this phase is indicated by another change in shape of the jet. Section 2 has formed a vortex and become the wide head of the jet, while Sections 3 and 4 form the jet tail, which is now cylindrical-to-conical in shape. The tail is disconnected from the vent as evidenced by the presence of ambient fluid between the vent and jet tail. The internal velocity structure of the jet re-organizes during this phase from the elongated pattern characterizing the cylindrical geometry to the compact radial pattern characterizing a spherical geometry [not shown; *Chojnicki et al*., 2015]. The original starting vortex V1 has moved completely independently of the tail, leaving the field of view.

3. Volcanic Plume Analysis

Although we cannot readily compare the internal velocity field results from Chojnicki et al., [2015] with observations of opaque volcanic plumes, we can compare the morphologies of our analogue jets to volcanic plumes. One study in the literature was suitable for this type of analysis because it provided information about the evolution of plume behavior and estimates for ash and gas contents. This study was from a hornito event at Stromboli and observed with an ultraviolet camera [*Mori and Burton*, 2009]. The plume observations (Panel b in Figures 1, 2 and 3) are modified from Mori and Burton [2009] and use a false-color scale where light grey represents high concentrations of sulfur dioxide and/or volcanic ash, dark grey represents lower concentrations, indicative of mixing of the plume fluid and ambient air, and black represents the zero concentration of pure ambient air.

Mori and Burton [2009] classify this event as Type 2 [*Patrick*, 2007], an ashy plume with a rise behavior that decelerates from an initially high velocity and then rises at a constant rate. These events are interpreted to have momentum as the primary driver during the initial stages when the flow-front propagation is decelerating [*Patrick*, 2007]. Thus, we assume buoyancy is not a dominant driver of the volcanic plume near the vent. Mori and Burton [2009] note that an ambient wind was present during this event, but given that the plume axis is near-vertical we argue that wind has at most a secondary effect in the initial rise process. We therefore assume our experimental results, with a neutrally buoyant jet rising into a still ambient, are analogous, at least to a first approximation.

For the first 8s of the Stromboli eruption (Figure 1b), a round head and a cylindrical tail characterize the plume morphology. The cylindrical tail can be subdivided into two sections: one with a width similar to the head (section 2) and one that has a smaller width (section 3). This simplified morphology is easy to distinguish in the volcanic plume images despite their greater complexity relative to the simple analogue jets. This morphology corresponds with Phase 1 in analogue jet evolution (Figure 1a), during which the vent discharge is increasing (source acceleration stage) [*Chojnicki et al*., 2015]. Thus, we also infer that the vent discharge rate is increasing during the first 8 s of this Stromboli. This inference is consistent with the interpretations of increasing gas flux made by Mori and Burton [2009]. We also observe in the laboratory experiments during Phase 1 that section 3 of the cylindrical tail has a similar diameter as the vent. We thus infer that the diameter of the volcanic plume tail (section 3) of ~6 meters is similar to the diameter of the volcanic vent. This inference is reasonably consistent with independent evidence that the hornito vents are approximately 2-5 meters wide [*Chouet et al*., 1974; *Vergniolle and Brandeis*, 1996; *Del Bello et al*., 2012].

We cannot state without uncertainty that the cylindrical shape of the jets during Phase 1 is uniquely indicative of an increasing discharge rate. However, we do assert that the cylindrical shape may be a good indicator of source unsteadiness, given that the cylindrical geometry appears in our analogue jets when the ejection is Gaussian in time, but cylindrical geometry is not observed when the source is steady as in Kitamura and Sumita [2011]. Given this ambiguity, future work should examine jet morphology response to a wide range of temporally varying discharge histories to determine if the cylindrical shape is unique to the discharge condition inferred here.

Snap shots of the Stromboli plume at 10s and 12s are shown in Figure 2b (right two panels). At these times a narrow neck of fluid begins to form between the head and tail of the volcanic plume. We infer this narrow region to be similar to the neck in the analogue jets that appears in Phase 2 (Figure 2a). This neck first appears when the discharge rate begins to decrease in the laboratory experiments [start of the falling edge of the Gaussian injection;

Chojnicki et al., 2015]. We therefore infer that the discharge rate has begun to decrease by this point in the volcanic eruption as well. This inference is not consistent with the interpretations of the gas flux made by Mori and Burton [2009], in which they conclude that discharge rate should still be increasing at this time. However, they assume that the total amount of sulfur dioxide in the image is a good proxy for the discharge conditions. We argue instead that the total amount of discharged sulfur dioxide (the amount in the images) is a proxy for the cumulative mass of fluid discharged from the beginning of the eruption until the time of the measurement, rather than a good indicator of the instantaneous discharge rate.

Snapshots of the plume from 14s to 20s are shown in Figure 3b. Although the shape of the plume near the volcanic vent is difficult to see, we note a rounded feature near the base of the plume, designated as the End Vortex (labeled EV) below which the plume narrows and nearly pinches out. The development of the EV is also observed in 'stopping jets' that are buoyant [*Kattimeri and Scase*, 2014]. In the analogue jet during Phase 3 (Figure 3a), there is also a gap between the base of the tail and the vent, while the EV is more difficult to observe. This gap appears between the vent and the EV in the volcanic plume (Figure 3b) and, thus, we interpret the EV to mark the end of the injection. The EV first appears at 12s (Figure 2b) in the volcanic eruption suggesting that the discharge rate decreased and ended around this time.

These combined observations indicate that the volcanic plume entered Phase 3 by approximately 14s after onset. In this phase of the analogue jets (Figure 3a), the starting vortex evolves independently of the tail. Evidence for this same independent motion in the volcanic plume is found in the difference in the concentrations between section 2 and V1 (Figure 3b); the concentration decreases over time in V1 but remains similar over time in section 2 and V1 appears to be moving or 'stretching' away from section 2. Furthermore, the concentration appears to decrease over time in sections 3 and 4 as well, but at a slower rate than the decrease in V1. These analogous observations of the laboratory jets indicate that the dynamics in different parts of the flow evolve somewhat independently in the later stages of the plume evolution. The spatial variations in plume evolution, and corresponding variations in plume dilution, are important considerations when modeling the dynamics of these plumes and resultant ash dispersal.

Phase 3 of the analogue jet evolution is marked by the particular characteristics of section 2, and the volcanic plume appears to follow a similar evolution (Figure 3). In Figure 3 section 2 appears to contain the highest fluid concentrations in both the laboratory (Figure 3a) and Stromboli (Figure 3b) flows. This pattern has implications for the transport of mass by the volcanic plume as it dissipates. In the laboratory case, and possibly also in the Stromboli case, the lower second structure appears to contain most of the mass within the plume, making the plume height an unreliable indicator of the height of the largest concentration of ash released to the atmosphere for subsequent downwind transport. Although, the difference in position between the second structure and flow front is small in this hornito event, it could be larger, and more significant, in larger short-duration events or as the plume evolves in time and grows in height.

In addition to the hornito event at Stromboli, we document the evolution of a single event at Santiaguito volcano in Guatemala (Figure 4), which is also known for generating short-duration explosive events, although the magma composition and thus exact eruption mechanisms are thought to vary between the two volcanoes. The images in Figure 4 were collected in January 2012 using a PlotWatcher Pro time-lapse camera sampling at 1 frame per second from the summit of Santia Maria.

We observe similar plume evolution at Santiaguito and Stromboli. The round front and tail regions of variable widths supply evidence for the generation of several features documented in the analogue jets - the starting vortex as well as the second, third, and fourth dynamic regions (as labeled in Figure 4). Unlike the Stromboli plume and analogue jets, however, no neck forms in the Santiaguito plume. The neck may not form for a variety of reasons including the absence of a discharge decrease in this event or perhaps the strong influence of buoyancy forces in the plume that cause section 2 to accelerate into V1, preventing the separation of the first structure from the second. Another characteristic unique to the Santiaguito plume is the appearance of the fourth dynamic region that is more cylindrical than conical. This region is identified here by the fact that its visible boundary is less clearly defined as compared with regions V1 through 3, possibly suggesting different dynamics at work in that region, such as a more gradual ending to the injection.

4. Conclusions

Under unsteady discharge conditions, analogue jets and short-eruption volcanic plumes evolve as a sequence of distinct flow segments. The segments grow in height and width, at various rates, as they rise. For analogue jets, changes in in the flow morphology can be correlated to changes in discharge conditions. Thus, the possibility exists to use changes in volcanic plume morphology as an indicator of changes in eruption discharge rate, and estimation of injection duration (and eventually mass eruption rate or total mass erupted) [*Chojnicki et al.*, 2015]. Inferring source conditions from relatively easy- and safe-to-collect plume observations may also reduce ambiguity in interpreting geophysical observations of eruption activity, when geophysical data is available, and provide a means of monitoring the evolution of eruption source conditions when geophysical data is not available or not available in real-time. Similar patterns of morphology evolution are observed for short-eruption volcanic plumes from Santiaguito and Stromboli volcanoes. We therefore suggest that plumes from short-lived eruptions with transient discharges will generally evolve in a similar way. More work on the effects of buoyancy and different discharge histories is needed to improve these inferences.

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Figure 1: (a) Analogue jet (white pixels) image characterizing Phase 1 of the jet evolution, modified from Chojnicki et al. [2015]. (b) False-color images of an evolving volcanic plume from a hornito event at Stromboli, modified from Mori and Burton [2009]. Light grey, dark grey and black indicate high, low and zero concentrations of sulfur dioxide/volcanic ash, respectively. Labels represent different dynamic regions of the flows: V1 is the starting vortex, sections 2 and 3 form the cylindrical tail with a cross sectional width similar to the head (2) and vent (3).

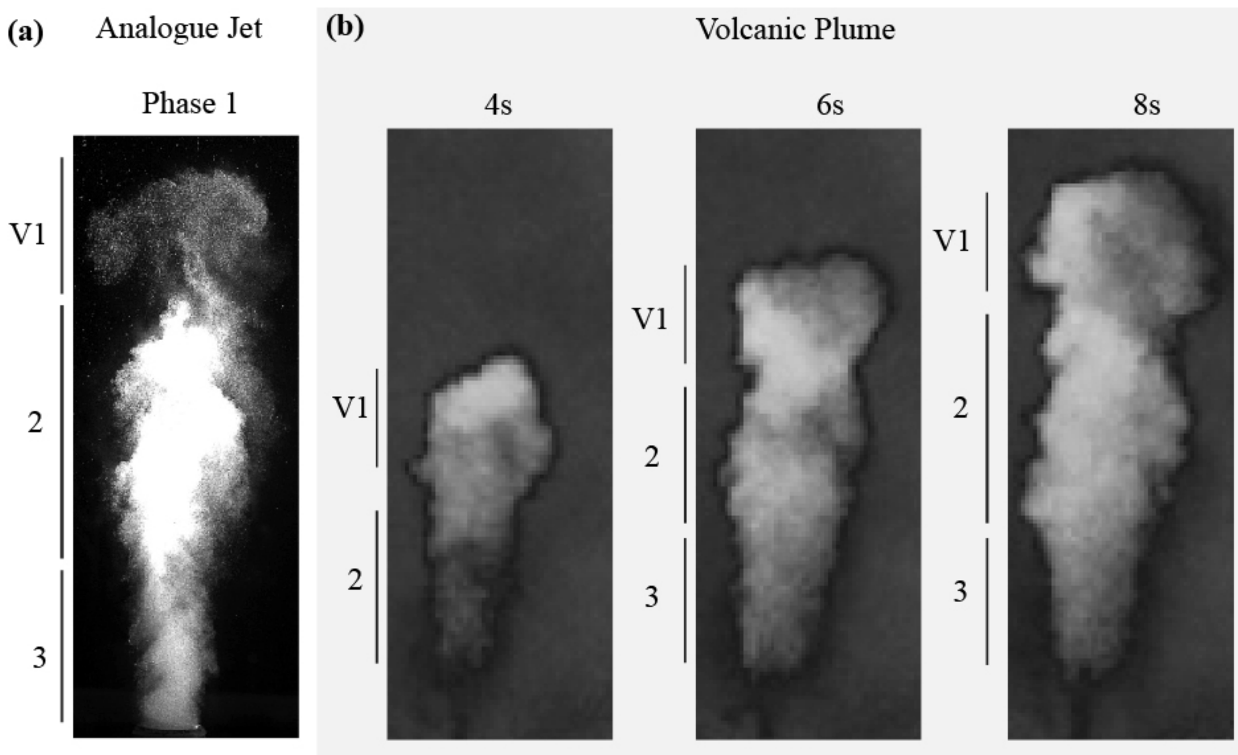

Figure 2: (a) The appearance of a ‘neck’ between sections V1 and 2 in analogue jets indicates the flow has entered phase 2 during which the discharge rate is decreasing [*Chojnicki et al*., 2015]. (b) The neck is also present in the volcanic plume at 12s [*Mori and Burton*, 2009] and, thus, we infer the discharge rate to be decreasing at that time.

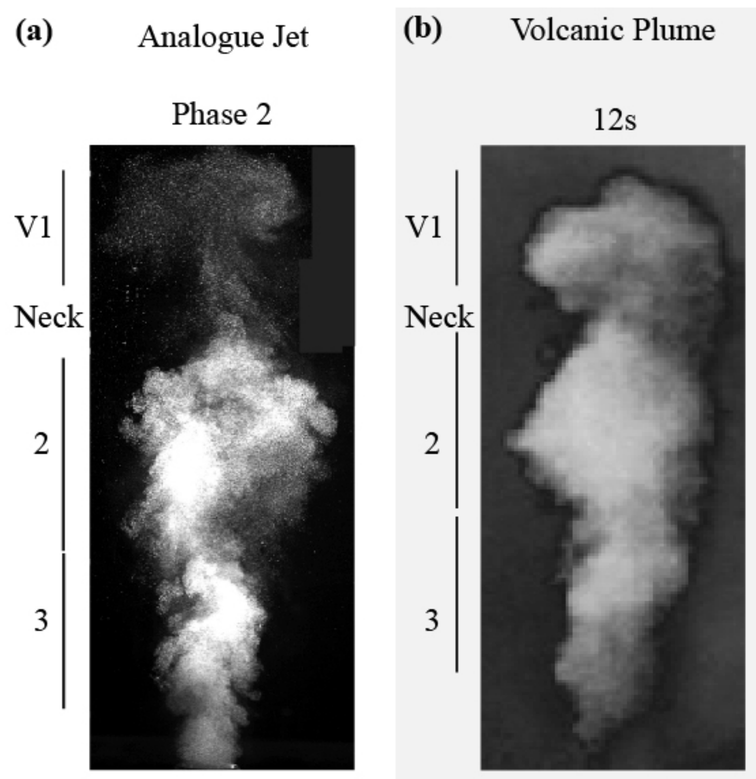

Figure 3. (a) In the analogue jets, the appearance of a narrow base, section 4, and a gap between the plume and the source indicates the discharge has ended and the flow is in Phase 3 [*Chojnicki et al*., 2015]. (b) In the Stromboli plume [*Mori and Burton*, 2009], this is difficult to see but an ending vortex (EV) may indicate then end of injection.

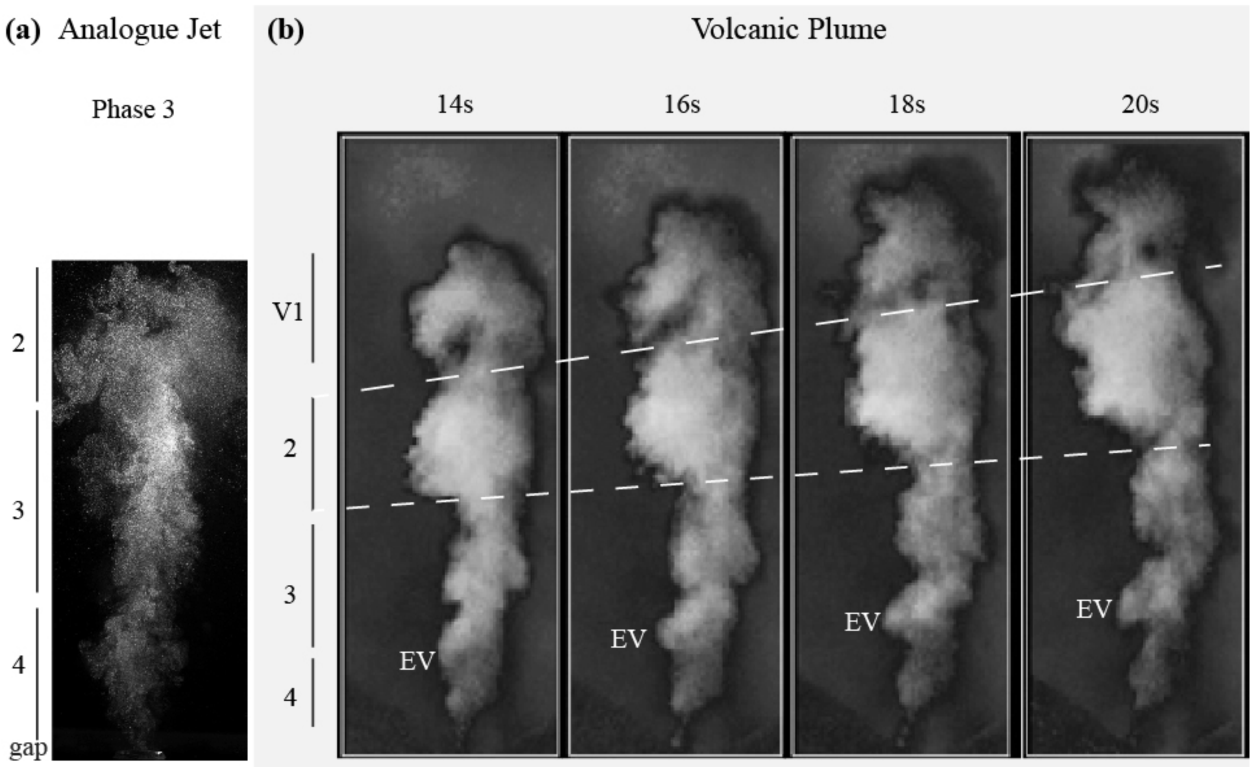

Figure 4. Snap shots of an evolving volcanic plume from Santiaguito volcano in Guatemala showing similar features to the analogue jets and the Stromboli plume, despite the differences in the volcanic systems.