Estimates of eruption velocity and plume height from infrasonic recordings of the 2006 eruption of Augustine Volcano, Alaska

Jacqueline Caplan-Auerbach *, Anna Bellesiles 1, Jennifer K. Fernandes 2

Western Washington University, Bellingham, WA, 98225, United States

A R T I C L E   I N F O

Article history:
Received 27 April 2009
Accepted 5 October 2009
Available online xxxx

Keywords:
eruption
plume
infrasound
acoustic

A B S T R A C T

The 2006 eruption of Augustine Volcano, Alaska, began with an explosive phase comprising 13 discrete Vulcanian blasts. These events generated ash plumes reaching heights of 3–14 km. The eruption was recorded by a dense geophysical network including a pressure sensor located 3.2 km from the vent. Infrasonic signals recorded in association with the eruptions have maximum pressures ranging from 13–111 Pa. Eruption durations are estimated to range from 55–350 s. Neither of these parameters, however, correlates with eruption plume height. The pressure record, however, can be used to estimate the velocity and flux of material erupting from the vent, assuming that the sound is generated as a dipole source. Eruptive flux, in turn, is used to estimate plume height, assuming that the plume rises as a buoyant thermal. Plume heights estimated in this way correlate well with observations. Events that exhibit strongly impulsive waveforms are underestimated by the model, suggesting that flow may have been supersonic.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

On January 11, 2006, after 20 years of quiescence and several months of volcanic unrest, Augustine Volcano erupted. In the two weeks that followed, Augustine released 13 discrete Vulcanian blasts, discharging gas and ash to heights exceeding 14 km. The eruption was exceptionally well monitored by a dense array of seismic and geodetic instruments as well as satellite data, near real time photography and visual observations (Power et al., 2006; Cervelli et al., 2006). Among the instruments located on the volcano itself was an infrasonic microphone which recorded all of the eruptive blasts as well as the continuous eruptive phase that followed. While the infrasonic signals accompanying the eruptions exhibited wide variations in peak amplitude and duration (Petersen et al., 2006), these signals did not correlate with the height of associated eruptive plumes.

In recent years, infrasonic recordings have been used to study a host of volcanic processes. Because path effects are less significant for atmospheric waves, infrasonic and acoustic signals are thought to be more informative about the eruptive source process and have been used by a multitude of researchers to investigate eruption source mechanics. Most infrasonic analysis has focused on discrete explosions such as Strombolian bubble bursts and gas eruptions (Vergniolle and Brandeis, 1994; Vergniolle and Brandeis 1996; Ripepe et al., 1996; Firstov and Kravchenko, 1996; Johnson and Lees, 2000; Vergniolle et al., 2004). Researchers have used infrasound to estimate the size and volume of magma bubbles (e.g. Vergniolle and Brandeis, 1996; Vergniolle et al., 2004), or to examine conditions during the uncorking of a volcanic conduit (Morrissey and Chouet, 1997; Johnson et al., 1998; Johnson and Lees, 2000). In some cases, infrasound has been critical in examining eruptions that could not be observed (Caplan-Auerbach and McNutt, 2003; Vergniolle and Caplan-Auerbach, 2006; Matoza et al., 2007; Moran et al. 2008).

While infrasound has been effective in studying signals such as magma bubble bursts, less use has been made of infrasonic signals recorded in association with ash eruptions. Infrasonic signals from ash bursts are typically prolonged, diffuse, and substantially more complicated than those associated with discrete blasts.

Woulff and McGetchin (1976) were among the first to investigate the acoustic signals associated with gas release at volcanoes. In their seminal paper, Woulff and McGetchin (1976) described a relation between acoustic pressure and the velocity of gases ejected from volcanic fumaroles. This formalism represents the base of the work presented here. We first discuss the method used to determine velocity from acoustic pressure and show how the method may be used to calculate eruption velocity and flux for Augustine eruptions. Finally we discuss how volume flux may be used to estimate plume heights, given certain assumptions about the mechanics of plume formation. Note that although the term “infrasound” specifically refers to signals below 20 Hz, the signals here carry some energy in the audible range (>20 Hz). Thus we use both “infrasonic” and “acoustic” in our discussion of the pressure signals recorded here.
2. Augustine Volcano and monitoring network

Augustine Volcano is an andesitic–dacitic stratovolcano that forms an island in Alaska's Cook Inlet. Although Augustine Island is unpopulated, it is located within 100 km of several population centers and its eruptions pose a significant hazard to aircraft and local shipping and oil refineries (Waythomas and Waitt, 1998). Augustine’s recent eruptions, occurring in 1976, 1986, and 2006, all exhibited similar progressions. Each event initiated as a series of discrete Vulcanian blasts, after which the volcano entered phases of continuous eruptive activity followed by effusion and dome growth (Coombs et al., in press; Waythomas and Waitt, 1998).

The Alaska Volcano Observatory has monitored seismic activity at Augustine since 1970. The 2006 eruption was recorded by a dense seismic and geodetic network (Cervelli et al., 2006). A Chaparral Model 21 infrasonic microphone was co-located with short period seismic station AUE at a distance of 3.2 km due east of Augustine's vent. A network of eight porous hoses was connected to the microphone to reduce noise. The microphone has a flat response at frequencies between 0.1 and 50 Hz and records both high and low gain channels with a dynamic range of 119 dB. This allows identification of small signals while also keeping large pressure signals on scale. All of the signals presented in this paper are a combination of these two channels: the high gain channel is used except where signals clipped (~13.5 Pa), in which case the data were replaced by values recorded on the low gain channel. Although the data are digitized at 16 bits, the combination of two channels gives the instrument an effective resolution of ~20 bits. The response of the Chaparral Model 21 has been tested at pressures exceeding 100 Pa, so we are confident that the signals recorded during the Augustine eruption are within the range for which the instrument was designed and for which its response is known.

The discrete blast phase of the 2006 eruption comprised 13 Vulcanian explosions accompanied by pyroclastic and debris flows (Coombs et al., in press). Each of the blasts was recorded on scale by the pressure sensor and the seismic network (Table 1). Maximum amplitudes range from 13 to 111 Pa at the pressure sensor, for sound pressure levels (SPL) of 117–133 dB (Petersen et al., 2006). Following the 13 blasts of the explosive phase, Augustine switched into a phase of continuous eruption, generating more or less constant block and ash flows for a period of 4 days (Coombs et al., in press). Background infrasonic levels are substantially higher for events 10 and 11, making the onset and coda of these events difficult to distinguish. This may be due to high winds, or to the volcano's transition near that time from discrete to continuous eruption. Thus, for consistency in the analysis we consider only the first 9 eruptive blasts in this study.

Waveforms for each of the nine eruptive events are presented in Fig. 1. Events 1–7 exhibit impulsive onsets while others have a more extended beginning. In most cases the event consists of a single burst of energy, although events 6 and 7 have a secondary amplitude increase several hundred seconds after the event begins.

3. Methodology

Fluctuations in air pressure recorded at a distance from a volcanic vent may be directly related to acoustic power, which in turn depends on flux at the volcanic vent (Woulff and McGetchin, 1976; Lighthill, 2001; Vergniolle and Caplan-Auerbach, 2006). The relation between eruptive flux and acoustic power, however, is complicated by uncertainties in the dynamics of the sound source. Woulff and McGetchin (1976) presented relations between velocity and power for three source types: monopole, dipole and quadrupole. A monopole source is one in which fluctuations in pressure are due entirely to the rate of change of mass flux, and is best envisioned as an expoding source. A steady gas jet or gas that interacts with solid walls is best described by a dipole source, the preferred model used by Woulff and McGetchin (1976) for describing gas release from volcanic fumaroles. Finally, gas sources that generate noise through turbulence, such as a jet engine, are modeled as quadrupoles.

For a source that radiates sound as a hemisphere of radius r, the relation between recorded pressure p and acoustic power Π is given by

$$\Pi = \frac{\pi r^2}{p_{air} c^4} \int_0^T |p - p_{air}|^2 \, dt$$

(1)

where \(p_{air}\) is air density, c is the speed of sound, \(T\) is the duration of the source function and \(p - p_{air}\) is the excess pressure (Table 2). The acoustic power depends strongly on the source function (monopole, dipole or quadrupole) and may be determined by one of the following functions (Woulff and McGetchin, 1976):

$$\Pi_m = k_m \frac{4\pi R^2 \rho_{air} u^4}{c}$$
$$\Pi_d = k_d \frac{\pi R^2 \rho_{air} u^6}{c^2}$$
$$\Pi_q = k_q \frac{\pi R^2 \rho_{air} u^8}{c^4}$$

(2)

where \(k_m, k_d\) and \(k_q\) are empirically derived constants, \(R\) is the source radius (here taken to be the radius of the volcanic conduit), \(u\) is the velocity of material at the source and \(c\) is the speed of sound in air (Table 2). The value of \(k_q\) is on the order of 1 while \(k_m\) and \(k_d\) are approximately \(10^{-2}\) and \(10^{-5}\) respectively (Vergniolle and Caplan-Auerbach, 2006). Thus, despite the exponential effect of velocity, for gas flowing at a given velocity, less sound will be generated by a quadrupole source than by a dipole or monopole. In an alternate view,

<table>
<thead>
<tr>
<th>Event</th>
<th>Date/time (UTC, 2006)</th>
<th>Maximum pressure (Pa)</th>
<th>Duration (s)</th>
<th>Max velocity (m/s)</th>
<th>Max flux ((m^2/s))</th>
<th>Eruptive volume ((10^7 m^2))</th>
<th>Modeled thermal height (km)</th>
<th>Sustained plume height (4% magma) (km)</th>
<th>Observed plume height (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jan 11, 13:44</td>
<td>96</td>
<td>55</td>
<td>196</td>
<td>5.5 × 10^2</td>
<td>1.0</td>
<td>6.8</td>
<td>17.0</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>Jan 11, 14:12</td>
<td>13</td>
<td>270</td>
<td>100</td>
<td>2.8 × 10^2</td>
<td>3.5</td>
<td>3.4</td>
<td>9.1</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Jan 13, 13:24</td>
<td>22</td>
<td>350</td>
<td>91</td>
<td>2.6 × 10^2</td>
<td>3.8 × 10^3</td>
<td>3.9</td>
<td>9.4</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Jan 13, 17:47</td>
<td>35</td>
<td>250</td>
<td>135</td>
<td>3.8 × 10^3</td>
<td>4.1</td>
<td>9.5</td>
<td>14.2</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Jan 13, 20:22</td>
<td>44</td>
<td>180</td>
<td>149</td>
<td>4.2 × 10^3</td>
<td>6.1</td>
<td>9.5</td>
<td>17.8</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>Jan 14, 01:00</td>
<td>33</td>
<td>270</td>
<td>132</td>
<td>3.7 × 10^3</td>
<td>6.1</td>
<td>10.5</td>
<td>17.8</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>Jan 14, 03:58</td>
<td>50</td>
<td>270</td>
<td>177</td>
<td>5.0 × 10^3</td>
<td>6.5</td>
<td>10.6</td>
<td>18.2</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>Jan 14, 05:14</td>
<td>62</td>
<td>150</td>
<td>189</td>
<td>5.3 × 10^3</td>
<td>4.5</td>
<td>9.7</td>
<td>15.1</td>
<td>N/A</td>
</tr>
<tr>
<td>9</td>
<td>Jan 17, 16:58</td>
<td>111</td>
<td>220</td>
<td>220</td>
<td>6.2 × 10^3</td>
<td>5.8</td>
<td>10.3</td>
<td>18.4</td>
<td>14</td>
</tr>
</tbody>
</table>

and one more relevant to the modeling described here, a low velocity signal behaving as a monopole would generate the same power as a quadrupole erupting at high velocity, as observed at a given distance from the vent.

Following Woulff and McGetchin (1976) and Vergniolle and Caplan-Auerbach (2006), we favor a dipole source for Augustine eruptions. The presence of conduit walls exerting a force on the erupting fluid as well as the interaction of fluid with solid particles within the flow, both of which are described by a dipole source, make this a reasonable choice for our model. The assumption of a dipole source, however, distinguishes our model from that of Johnson (2007) who determined that pyroclastic explosions at Karymsky volcano are best described by a monopole source. Although both Augustine and Karymsky exhibited small explosive blasts, their associated infrasonic signals differ dramatically. Augustine’s events were substantially larger, with pressures exceeding 100 Pa at 3.2 km from the vent, as compared to maximum pressures of ~8 Pa at 1.8 km from the vent at Karymsky (Johnson, 2007). Karymsky’s infrasonic signals lasted several seconds, while at Augustine’s sound was recorded for several tens of seconds. Finally, Augustine plumes rose to significantly greater heights (9–14 km) than those observed at Karymsky (<1 km). This combination of parameters suggests that the source mechanics for these two eruptions were significantly different.

Our contention that the data are best described by a dipole also differs from Matoza et al. (2009) who contend that eruption sound has its source in large scale turbulence akin to jet noise. The eruptions described by Matoza et al. (2009), however, generated acoustic signal for durations of hours whereas infrasonic recordings of Augustine blasts return to background levels within minutes despite the fact that photos indicate the plumes remained suspended for substantially longer periods. Similarly, infrasound levels at Augustine were very low on January 29, 2006, when web camera images show a turbulent plume and pyroclastic flows on Augustine’s flanks (Fig. 2). Thus infrasound at Augustine appears to be generated during the gas thrust phase of eruption, not from turbulent flow within the plume. This argues against a quadrupole source.

In our calculation of acoustic power we take the speed of sound in air to be 330 m/s (Table 2). Although we do not know the density of the eruptive material, we know that most of the explosions were not associated with column collapse, so the plumes were generally buoyant. Density during the gas thrust region, however, may exceed that of air if the vent is overpressurized (e.g. Ogden et al., 2008). Throughout this paper we assume that the eruption took place at atmospheric pressure but discuss the effect on the model of vent overpressure.

For each blast of the Augustine eruption we use recorded infrasonic pressures to calculate a time series of gas velocity (Fig. 3).

Table 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Value/units</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Π</td>
<td>Acoustic power</td>
<td>3.2 km</td>
<td>Woulff and McGetchin, 1976; Vergniolle and Caplan-Auerbach, 2006</td>
</tr>
<tr>
<td>r</td>
<td>Source–receiver distance</td>
<td>30 m</td>
<td>Coombs et al. (in press)</td>
</tr>
<tr>
<td>ρ</td>
<td>Air/plume density</td>
<td>0.8, 4 g/cm³</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>Speed of sound in air</td>
<td>330 m/s</td>
<td></td>
</tr>
<tr>
<td>τ</td>
<td>Signal duration</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>Excess pressure recorded at sensor (relative to air pressure p₀)</td>
<td>Pa</td>
<td></td>
</tr>
<tr>
<td>Kᵢₒ, K₉, Kₜ</td>
<td>Empirical constants</td>
<td>1; 10⁻², 10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>Vent radius</td>
<td>30 m</td>
<td></td>
</tr>
<tr>
<td>u</td>
<td>Eruption velocity</td>
<td>m/s</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>Total eruptive volume flux</td>
<td>m³/s</td>
<td></td>
</tr>
<tr>
<td>Q_magma</td>
<td>Magma volume flux</td>
<td>1–15% of total eruptive volume flux (m³/s)</td>
<td></td>
</tr>
<tr>
<td>H_p, H_T</td>
<td>Heights of sustained plume and buoyant thermal</td>
<td>km, m</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Brunt–Väisälä frequency</td>
<td>0.003 Hz</td>
<td>Collins et al. (2008)</td>
</tr>
<tr>
<td>Vₐ, T₀</td>
<td>Total eruptive volume, eruption temperature, air temperature</td>
<td>m³, 1100 K; 273 K</td>
<td>Larsen et al. (2009)</td>
</tr>
</tbody>
</table>

Fig. 1. Time series of acoustic pressure from the first nine eruptive bursts. Note that the vertical scales vary. Some events exhibit impulsive onsets while others have a more prolonged beginning. The second amplitude peak recorded during event 7 (at ~200 s) may be a flow event.
Velocities are calculated for two-second windows; sensitivity tests indicate that velocities fluctuations are well-captured for windows up to ~5 s.

The methodology described above allows us to determine the velocity of material exiting the vent. This provides the opportunity to determine the volume flux of material exiting the vent. Assuming that material is ejected from a circular vent of radius $R$, and given the time series of velocity shown in Fig. 3, we estimate the volume flux of gas:

$$Q = \pi R^2 u.$$  

(3)

After Coombs et al. (in press), we take the radius of the vent to be 30 m. Note that Eq. (3) yields a volume flux. Conversion to mass flux requires assumptions about the density of the plume which is poorly constrained. However, the model is not strongly dependent upon this value, as discussed below.

Fig. 3 shows time series of velocity and volume flux for each of the nine eruptive bursts assuming a dipole source. Eruption velocity jumps sharply to 100–220 m/s, then smoothly tapers over several hundred seconds. These velocities are consistent with other studies performed on Vulcanian eruptions (Self et al., 1979; Clarke et al., 2002; Formenti et al., 2003). Because flux is simply velocity times the constant cross-sectional area of the vent (Eq. (3)), the same function, scaled by area, represents volume flux. We performed the same calculation with monopole and quadrupole sources and found that for a monopole source velocities range from 20–80 m/s while a quadrupole source is modeled to have velocities between 200–500 m/s.

Assuming a dipole source, no significant vent overpressure, and the velocity–flux relation presented in Eq. (3), the eruptive volume flux for Augustine eruptions is found to be $2.6–6.2 \times 10^{6} \text{m}^3/\text{s}$ (Fig. 3, Table 1). The duration of the eruptive burst is estimated from the acoustic record, allowing us to estimate the total eruptive volume for each blast. Eruptive volumes range from 1.0 to 6.5 $\times 10^{5}$ m$^3$. The total volume for the nine eruptive bursts presented here is $4.8 \times 10^{8}$ m$^3$.

These values can be compared with volume estimates for pyroclastic flows, debris flows and ash fall (Coombs et al., in press). Because geologists had limited access to eruptive products during the explosive phase of the eruption, Coombs et al. (in press) present cumulative dense rock equivalent (DRE) volumes for events 3–8. The cumulative DRE for this period is estimated at $12.1 \times 10^{6}$ m$^3$. Eliminating events 1, 2 and 9 from our calculations yields a total eruptive volume of $2.9 \times 10^{5}$ m$^3$. Thus the cumulative DRE represents just over 4% of the total eruptive volume, indicating that ~96% of the plume volume was gas. Note that if vent pressure is taken to be four times atmospheric pressure (e.g. Ogden et al., 2008), the total eruptive volume is found to be $1.7 \times 10^{6}$ m$^3$. Under these conditions, cumulative DRE represents nearly 7% of the plume volume at the time of eruption. Larger values of vent overpressure yield correspondingly greater densities.

4. Plume height from gas flux

Volcanic eruptions are associated with a variety of seismic and acoustic signals related to the interaction between the erupting jet and the ground or atmosphere. McNutt (1994) identified an apparent correlation between the amplitude of seismic tremor and the Volcanic Explosivity Index (VEI). However, because VEI includes a variety of parameters, only one of which is plume height, this correlation offers no predictive model for column height. In a study of seismoacoustic signals associated with Vulcanian blasts at Tungurahua volcano (Ecuador), Johnson et al. (2005) identified little correlation between the amplitude of the seismic and acoustic signals and the height of the eruption plume. Similarly, although Johnson (2007) showed a correlation between acoustic intensity and muzzle velocity for small blasts at Karymsky, differences in the appearance of the infrasonic coda were poorly matched with plume behavior. From the perspective of volcanic monitoring this is frustrating; observatories have traditionally been unable to estimate the hazard associated with eruptive plumes by looking at the amplitude of associated seismic and infrasonic signals.

Estimates of eruptive flux, however, provide a means by which the height of eruption plumes may be estimated. Sparks et al. (1997) describe relations between eruptive volume flux and plume height for two scenarios: a plume that is continuously fed at the vent and a thermal, or discrete plume. For a plume that is sustained at the vent, which is to say the eruption duration comprises a large portion of the plume’s rise time, Sparks et al. (1997) empirically show that the plume height may be determined by

$$H_p = 1.670.259Q_{\text{magma}}$$

(4)

where $H_p$ is column height in km and $Q_{\text{magma}}$ is the volume flux of magma during the eruption.

Fluxes determined with infrasound data represent the volume of all erupted material, not simply magma. While we know the estimated

Fig. 2. Time series of high gain infrasound from January 29, 2006, correlated with webcam photos. A plume is visible emanating from Augustine’s summit while a second plume, presumably from a pyroclastic flow, is visible slightly behind the volcano. Although there is significant plume activity, acoustic amplitudes are low, suggesting that the source of sound is not turbulence within the plume. Unfortunately no web camera images are available prior to 01:07 UTC when infrasonic amplitudes were higher.
DRE for plumes 3–8 (Coombs et al., in press), we do not have these values for each event. However, as noted above, comparisons of total eruptive volume with the DRE volume suggest that magma comprises only a few percent of the total volume of material erupted in each plume. We therefore calculate estimated plume heights for discharge rates ranging from 1–15% of the total volume (Fig. 4). Because we estimate that the magma represents 4% of the total erupted volume, plume heights for 4% are plotted in Fig. 4 as larger symbols. We stress, however, that discharge rates are uncertain in these continuous plume models.

If the rise time of a plume is long relative to the duration of the eruption, plume rise is controlled by thermal buoyancy and entrainment of surrounding air. In this case the height of the thermally buoyant plume \( H_T \) is given by

\[
H_T = 2.7F_T^{1/4}N^{1/2}
\]

where \( F_T \) is the product of plume buoyancy and volume and is determined by

\[
F_T = V_{To}g\left(\frac{T_{To} - T_a}{T_a}\right).
\]

In this formalism \( T_{To} \) and \( T_a \) are the initial temperature of the plume and the air temperature, respectively, and are given in units of Kelvin. \( V_{To} \) is the initial volume of the thermal and \( g \) is the acceleration due to gravity. The variable \( N \) in Eq. (5) is the Brunt–Väisälä frequency, also known as the buoyancy frequency of the atmosphere. In this study we assume that the temperature of the eruptive material is 1173 K (Larsen et al., 2009) and the atmospheric temperature is assumed to be 273 K. The eruptive volume is determined from the output of the flux analysis, as described above (Table 1).

Because of the relative strengths of \( F_T \) and \( N \) in Eq. (5), it is clear that the height of a thermal is strongly dependent upon the response of the atmosphere to a rising plume. The Brunt–Väisälä frequency depends on the thermal profile of the atmosphere and is therefore somewhat seasonally dependent. In general, the Brunt–Väisälä frequency varies from ~0.001 to 0.01 Hz globally. A recent LiDAR study of the Arctic atmospheric suggests that the buoyancy period for Alaska winter is ~300–370 s, the inverse of which yields a Brunt–Väisälä frequency of 0.0027–0.0033 Hz (Collins et al., 2008). Thus in this study we use a value of 0.003 Hz. This is also consistent with the work of Kanamori (2004) in a study of atmospheric gravity waves associated with the 1991 eruption of Mt. Pinatubo volcano, Philippines. After Larsen et al. (2009) we take the initial temperature of the eruption plume to be 900 °C and we assume an air temperature of 0 °C (Table 2). The initial volume of the plume is taken from the integrated gas flux over the duration of the eruption (Table 1).

Plume heights calculated for the continuous eruption model dramatically overpredict eruption heights (Table 1 and Fig. 4). If the
gas fluxes determined by our acoustic model are accurate, sustained
generation of these fluxes should theoretically result in plumes
exceeding 20 km in height. These predictions are several times larger
than any plumes observed during the Augustine eruption. This
observation supports the Vulcanian description of Augustine plumes;
there is no evidence that eruptive blasts at Augustine were prolonged.

If the Augustine explosive events are assumed to behave as
buoyant thermals, a model that is pressure balanced at the vent (no
overpressure) predicts that they will rise to heights of 6.8–10.6 km,
compared with the 9–14 km observed during the eruption (Fig. 4).
The root-mean-square (rms) misfit between observation and predic-
tion is 1.5 km. The largest misfits between model and observed plume
heights are for plumes 1 and 9 where our model underpredicts plume
heights by ~2–3 km. Inspection of the acoustic signals associated with
these events reveals that these two signals exhibited the strongest
pressure signals recorded during the explosive phase of the eruption:
96–111 Pa at 3.2 km from the vent. The waveforms of these blasts also
exhibit extremely impulsive waveforms (Fig. 1). Finally, these events
had two of the fastest eruption velocities, at 196 and 220 m/s for
events 1 and 9 respectively (Fig. 3). The combination of impulsive
waveforms, strong pressure signals and high eruption velocities
suggests that events 1 and 9 may have been supersonic, in which case
the acoustic approximation of small pressure oscillations breaks down
and the model presented here becomes invalid. Event 8 has a similarly
high eruption velocity and impulsive waveform, but no data are
available for the height of its eruption plume and thus we cannot
compare it to our model.

The one blast for which our model results in a substantial (1.7 km)
overprediction of plume height is event 7 (Fig. 4). This particular
acoustic signal has a large secondary pulse occurring ~100 s after
the first sound (Fig. 1). It is possible that this secondary signal was
associated with a pyroclastic flow event and not with flux at the vent.
Because our model assumes the entire acoustic signal results from
vent flux, this would result in an overprediction of eruptive flux and
hence plume height. Coombs et al. (in press) note that pyroclastic
flow deposits were observed following events 7 and 8. The height of
the plume generated by eruptive event 8 is unknown, but the acoustic
signal is of relatively short duration and bears similarity to events 2, 4
and 5 which are fairly well predicted by our model.

5. Sensitivity analyses

As noted above, our model is not strongly dependent on the
density of the plume. To confirm this, we calculated eruptive
velocities and predicted thermal heights for two cases: one in which
material erupts at atmospheric pressure and one where vent
overpressure is four times the atmospheric pressure (Ogden et al.,
2008). In this situation, eruptive material has four times the density
of air and thermal buoyancy carries it to slightly lower heights. However,
the difference is slight: the less dense plume only rises 1.1 km higher
on average than the overpressurized, denser plume. At a vent
overpressure of 10 atm, the heights predicted for thermals are nearly
3 km below that observed. In contrast, greater overpressure means
that magma comprises a larger percent of the eruptive flux (gas in the
plume is more dense). Under these conditions, a sustained plume
would rise even higher than the values shown in Fig. 4.

We have made the assumption that the behavior of Augustine's
plumes is that of a dipole. If instead we model the eruption as a
monopole, the model preferred by Johnson (2007) for small eruptions
at Karymsky, we find lower eruption velocities and correspondingly
lower thermal heights. In contrast, use of a quadrupole source yields
substantially higher velocities and higher modeled plume heights. The
rms misfit for a dipole source is 1.8 km; in contrast, heights for a
monopole source underpredict observations by ~3.3 km while
modeling of a quadrupole yields plume heights that average 2.3 km
too high.

Because our modeled plume heights depend on the eruptive
volume flux, and because the flux is a function of the vent area, our
estimate of vent radius has perhaps the most significant effect on the
model. If we take the vent radius to be 20 rather than 30 m, the model
underpredicts plume height by an average of ~2.3 km. This increases
to a misfit of nearly 3.8 km for a vent radius of 10 m. In this study we
base our estimate of vent radius on observations of the size of
Augustine's lava dome, as well as models of plume volume, as
described by Coombs et al. (in press). However, this illuminates the
extent to which the model relies on well-constrained vent geometry.

6. Conclusions

The amplitude and duration of seismic and acoustic signals
associated with eruptions have been shown to poorly correlate with
eruption plume height. The model presented here, however, confirms
that gas flux, as determined by analysis of acoustic data, serves as a
good indicator of the height to which a plume is likely to rise.
Unfortunately, of the 13 plumes generated during the explosive stage
of Augustine's 2006 eruption, only two events, events 9 and 11, lie
outside of the 8–11 km range. These events are important to
determine whether our model works for endmember cases, or
whether it predicts similar heights regardless of each event's specific
characteristics. As previously noted, event 9 is modeled to have the
fastest eruption velocity, which, combined with the impulsive nature
of the infrasonic waveform, strongly suggests that the eruption was
supersonic. And event 11, the smallest of the eruption plumes, occurs
at a time when there was significant acoustic noise thought to be
associated with pyroclastic flows or wind. However, highpass filtering
of the event 11 waveform removes the long period background noise
and allows us to estimate the velocity, flux and thermal height for that
event. Using filtered data and a duration of 20 s, we find an eruption
velocity of 129 m/s, a maximum flux of 3.6 x 10^3 m^3/s, yielding a
predicted thermal height of 3.0 km, an excellent match to the
observed height of <3 km (Petersen et al., 2006). Furthermore, it is
substantially lower than any of the other modeled thermal heights,
lending credence to the model.

We show that acoustic data recorded in association with Vulcanian
eruptions can be used to estimate eruption velocity, volume flux at the
vent, and, for plumes with short durations (thermals), eruption plume
heights by ~2 km. This increases to a misfit of nearly 3.8 km for a
vent radius of 10 m. In this study we base our estimate of vent radius on observations of the size of
Augustine's lava dome, as well as models of plume volume, as
described by Coombs et al. (in press). However, this illuminates the
extent to which the model relies on well-constrained vent geometry.

Please cite this article as: Caplan-Auerbach, J., et al., Estimates of eruption velocity and plume height from infrasonic recordings of the 2006
heights. Maximum eruption velocities are found to be 93–220 m/s with volume fluxes on the order of 10^8 m^3/s. Assuming the plume rises as a buoyant thermal, the maximum plume height is found to be within <2 km of the observed height for six of eight plumes for which plume heights were observed. The model underpredicts plume heights for supersonic eruptions, as the assumption of small acoustic oscillations breaks down.

Acknowledgments

We are strongly indebted to Sylvie Vergniolle of the Institut de Physique du Globe de Paris for sharing her scripts for the calculation of acoustic power and eruptive velocity. The manuscript benefited from thoughtful and thorough reviews by Jeff Johnson and Maurizio Ripepe as well as conversations with Michelle Coombs of the USGS/Alaska Volcano Observatory. This project initiated as Anna Bellesies’ and Jennifer Fernandes’ undergraduate senior thesis at Western Washington University.

References


