Local infrasound observations of large ash explosions at Augustine Volcano, Alaska, during January 11–28, 2006

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[1] We present and interpret acoustic waveforms associated with a sequence of large explosion events that occurred during the initial stages of the 2006 eruption of Augustine Volcano, Alaska. During January 11–28, 2006, 13 large explosion events created ash-rich plumes that reached up to 14 km a.s.l., and generated atmospheric pressure waves that were recorded on scale by a microphone located at a distance of 3.2 km from the active vent. The variety of recorded waveforms included sharp N-shaped waves with durations of a few seconds, impulsive signals followed by complex codas, and extended signals with emergent character and durations up to minutes. Peak amplitudes varied between 14 and 105 Pa; inferred acoustic energies ranged between $2 \times 10^8$ and $4 \times 10^8$ J. A simple N-shaped short-duration signal recorded on January 11, 2006 was associated with the vent-opening blast that marked the beginning of the explosive eruption sequence. During the following days, waveforms with impulsive onsets and extended codas accompanied the eruptive activity, which was characterized by explosion events that generated large ash clouds and pyroclastic flows along the flanks of the volcano. Continuous acoustic waveforms that lacked a clear onset were more common during this period. On January 28, 2006, the occurrence of four large explosion events marked the end of this explosive eruption phase at Augustine Volcano. After a transitional period of about two days, characterized by many small discrete bursts, the eruption changed into a stage of more sustained and less explosive activity accompanied by the renewed growth of a summit lava dome. Citation: Petersen, T., S. De Angelis, G. Tytgat, and S. R. McNutt (2006), Local infrasound observations of large ash explosions at Augustine Volcano, Alaska, during January 11–28, 2006, Geophys. Res. Lett., 33, L12303, doi:10.1029/2006GL026491.

1. Introduction

[2] Augustine Volcano is a 1260 m high cone-shaped island stratovolcano located in southern Cook Inlet, Alaska. Historical Augustine activity has been characterized by vigorous explosion events that produced ash clouds and pyroclastic flows, small lava flows and extrusion of lava domes. On January 11–28, 2006, Augustine’s most recent eruption exhibited 13 large explosive events with durations of 1 to 11 minutes that produced ash-rich plumes reaching heights of up to 14 km a.s.l. The explosion events generated strong infrasonic signals that were recorded on scale by a newly installed microphone located on the volcano.

[3] In the last ten years, microphones located on many active volcanoes around the world have revealed a large variety of infrasonic signals associated with different styles of volcanic degassing [Johnson et al., 2004b]. For example, infrasonic degassing signals recorded at Stromboli [Vergniolle et al., 1996] and Erebus [Rowe et al., 2000] exhibited waveforms that are characterized primarily by a single, short-duration sinusoidal pulse associated with bubble bursts at the surface of a low-viscosity fluid body. In contrast, Arenal [Hagerty et al., 2000], Karymsky and Sangay [Johnson and Lees, 2000] revealed complex codas lasting several minutes indicative of extended-duration degassing associated with Strombolian explosions in higher-viscosity volcanic systems.

[4] The objective of this paper is to describe the strong infrasonic signals associated with the Vulcanian-style eruptions that occurred in the period January 11–28, 2006 at Augustine Volcano. The acoustic data gathered during this sequence of explosive eruptions exhibit some unique features in comparison to other case studies found in the literature. This data set provides one of the few examples of continuous monitoring of an entire eruptive sequence by use of a local sensor, as opposed to temporary campaigns where microphones are deployed for periods of days to weeks. In conjunction with Augustine infrasound recorded in the far-field (infrasound array I53US, Fairbanks) the data set offers a unique opportunity for the infrasound community to enhance studies of acoustic propagation. Furthermore, the data set provides observations for a type of eruption that is not frequently studied with acoustic sensing. Previous acoustic studies have mainly focused on Strombolian explosions, but also on lava lake degassing (e.g., Erebus [Rowe et al., 2000]), silicic dome building eruptions (e.g., Santiaguito [Johnson et al., 2004a]), and Subplinian plumes (e.g., Shishaldin [Vergniolle and Caplan-Auerbach, 2005]). The eruptive activity at Augustine Volcano presents a rare case of waveforms associated with vigorous and continuous degassing activity during an energetic Vulcanian-type eruption.

2. Data Acquisition

[5] On January 4, 2006, we deployed a Chaparral Model 2.1 microphone at site AUE on the volcano’s ENE flank at a direct distance of 3.2 km from the active summit vent (Figure 1). The well calibrated pressure transducer system, consisting of the microphone, a Voltage Controlled Oscillator (VCO) and a discriminator, has a flat response between 0.1 and 50 Hz. In addition to a high-gain channel the system is equipped with a low-gain component that allows record-
Figure 1. Map of Augustine Volcano showing the permanent AVO monitoring network stations including broadband seismic station AUL and the pressure sensor co-located with a short-period seismic station at AUE (white circles). The active vent is located at the summit. The 4 summit stations and AUL were destroyed over the course of the eruption. Image modified from map provided by E. Thoms/USGS.

The acoustic signals recorded at station AUE during the January 2006 Augustine explosive activity had peak amplitudes ranging from 14 to 105 Pa (Figure 2). Following a large pulse that accompanied the onset of the eruption phase on January 11, 2006, a sequence of events with increasingly larger peak pressures was recorded; the largest pulse was recorded on January 28, 2006 at 08:37:47 UT. The values of the eruption events.

### Table 1. Parameters of Augustine January 11–28, 2006 Explosive Eruption Events

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Date, UT</th>
<th>Event Onset, UT</th>
<th>Acoustic Onset, UT</th>
<th>Type</th>
<th>Pa</th>
<th>D&lt;sub&gt;acoustic&lt;/sub&gt;, s</th>
<th>Energy, J</th>
<th>SPL, dB</th>
<th>AUL Onset</th>
<th>Plume Height, km</th>
<th>Pa Recorded at I53US&lt;sup&gt;a,b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11-Jan</td>
<td>13:44</td>
<td>13:44:55</td>
<td>I</td>
<td>93</td>
<td>25</td>
<td>5.8 x 10&lt;sup&gt;8&lt;/sup&gt;</td>
<td>133</td>
<td>25</td>
<td>9</td>
<td>0.09</td>
</tr>
<tr>
<td>2</td>
<td>11-Jan</td>
<td>14:12</td>
<td>14:12:29</td>
<td>E</td>
<td>14</td>
<td>100</td>
<td>2.1 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>117</td>
<td>150</td>
<td>9</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>13-Jan</td>
<td>13:24</td>
<td>13:19:51</td>
<td>E</td>
<td>22</td>
<td>130</td>
<td>5.3 x 10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>120</td>
<td>500</td>
<td>10</td>
<td>0.04</td>
</tr>
<tr>
<td>4</td>
<td>13-Jan</td>
<td>17:47</td>
<td>17:48:27</td>
<td>E</td>
<td>35</td>
<td>100</td>
<td>9.4 x 10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>124</td>
<td>300</td>
<td>&gt;9</td>
<td>0.09</td>
</tr>
<tr>
<td>5</td>
<td>20-Jan</td>
<td>20:22</td>
<td>20:22:15</td>
<td>I</td>
<td>32</td>
<td>150</td>
<td>14.6 x 10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>124</td>
<td>300</td>
<td>11</td>
<td>0.16</td>
</tr>
<tr>
<td>6</td>
<td>14-Jan</td>
<td>01:40</td>
<td>01:40:38</td>
<td>E</td>
<td>29</td>
<td>150</td>
<td>14.3 x 10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>123</td>
<td>280</td>
<td>10</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>14-Jan</td>
<td>03:58</td>
<td>03:58:15</td>
<td>E</td>
<td>52</td>
<td>170</td>
<td>38.0 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>128</td>
<td>300</td>
<td>9</td>
<td>0.08</td>
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<tr>
<td>8</td>
<td>14-Jan</td>
<td>09:14</td>
<td>09:13:37</td>
<td>I</td>
<td>65</td>
<td>100</td>
<td>27.0 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
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<td>200</td>
<td>No data</td>
<td>0.23</td>
</tr>
<tr>
<td>9</td>
<td>17-Jan</td>
<td>16:58</td>
<td>(16:58:28)</td>
<td>E+</td>
<td>93</td>
<td>50</td>
<td>36.1 x 10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>133</td>
<td>200</td>
<td>14</td>
<td>0.21</td>
</tr>
<tr>
<td>10</td>
<td>28-Jan</td>
<td>05:24</td>
<td>(05:31:05)</td>
<td>E+</td>
<td>83</td>
<td>250</td>
<td>38.5 x 10&lt;sup&gt;3&lt;/sup&gt;</td>
<td>132</td>
<td>No data</td>
<td>&lt;3</td>
<td>0.10</td>
</tr>
<tr>
<td>11</td>
<td>28-Jan</td>
<td>08:37</td>
<td>08:37:47</td>
<td>I</td>
<td>105</td>
<td>20</td>
<td>7.1 x 10&lt;sup&gt;3&lt;/sup&gt;</td>
<td>134</td>
<td>No data</td>
<td>&lt;3</td>
<td>0.10</td>
</tr>
<tr>
<td>12</td>
<td>28-Jan</td>
<td>11:04</td>
<td>11:04:26</td>
<td>I</td>
<td>66</td>
<td>150</td>
<td>21.5 x 10&lt;sup&gt;3&lt;/sup&gt;</td>
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<td>0.42</td>
</tr>
<tr>
<td>13</td>
<td>28-Jan</td>
<td>16:42</td>
<td>16:48:24</td>
<td>E</td>
<td>24</td>
<td>160</td>
<td>20.4 x 10&lt;sup&gt;3&lt;/sup&gt;</td>
<td>121</td>
<td>No data</td>
<td>8</td>
<td>0.10</td>
</tr>
</tbody>
</table>

<sup>a</sup> AVO official start of eruption event based on seismic data.
<sup>b</sup> Acoustic arrival times within ±1 s accuracy picked at AUE; times in () indicate arrival of low-amplitude phase that precedes main pulse.
<sup>c</sup> Waveform category “impulsive” (I) and “emergent” (E).
<sup>d</sup> Maximum zero-to-peak pressure [Pa].
<sup>e</sup> Duration of acoustic and seismic traces recorded at AUE and AUL, respectively, measured from signal onset until amplitude has decayed to background levels; AUL stopped functioning on January 28; listed acoustic duration was used for energy calculations.
<sup>f</sup> Sound pressure level $SPL = 20 \log(\Delta P/2 \times 10^{-5})$ [Johnson, 2003] of atmospheric pressure perturbations ($\Delta P$) recorded at station AUE relative to background atmospheric pressure (~10<sup>5</sup> Pa).
<sup>g</sup> Approximated by the National Weather Service based on radar data.
<sup>h</sup> Pressure signal (0-to-peak) [Pa] recorded at infrasound array I53US in Fairbanks (C. R. Wilson, personal communication, 2006).
this explosive eruption phase exhibit no apparent correlation with the corresponding acoustic peak pressures. Following January 28, 2006, the occurrence of many small discrete explosions (0-peak pressures of 0.5–1 Pa; only distinguishable from noise on the high-gain channel) characterized a period that lasted about two days, and that marked the transition of the eruption to a more continuous and less explosive stage of activity. In Table 1, we report peak amplitudes for the various explosion events as recorded at station AUE, and the respective sound pressure levels (SPL) as measured in the infrasonic bandwidth.

[9] It is worth noting that the acoustic pulses associated with the explosive phase were large enough to be recorded by the infrasound array I53US located in Fairbanks, Alaska (at 675 km from the volcano); zero-to-peak amplitudes ranged from 0.04 to 0.42 Pa (Table 1) and signal root-mean-square values between 0.0103 and 0.0796 Pa [Wilson et al., 2006].

[10] The waveforms recorded at AUE exhibit a great variety of different characteristics; representative examples are shown in Figure 3. Although individual events differ significantly from each other, we can group them into two broad categories based on the appearance of the initial phase: “emergent events” and “impulsive events”. The two groups share a largely similar frequency content with the bulk of acoustic energy confined between 0.1 and 5 Hz. The “emergent events” are characterized by gradually increasing initial phases that reach peak amplitudes of 14–52 Pa before slowly tapering off (e.g., Figure 3b); typical time durations are 100–170 s.

[11] The “impulsive events” exhibit a sharp large-amplitude compression followed by a rarefaction; this characteristic N-shaped phase is followed by a lower amplitude coda.

Figure 2. Zero-to-peak pressures of the 13 acoustic signals associated with the explosive eruption phase (January 11–28, 2006). Preliminary plume heights determined by NWS are indicated by dots. Horizontal axis is event number, with dates shown at the top.

Figure 3. Examples of traces and cumulative energies of acoustic signals associated with the Augustine January 2006 explosive eruptions recorded at AUE. The signals are high-pass filtered with a corner frequency of 0.1 Hz. (a, c, and d) “impulsive events”; (b) an example for an “emergent event”. Note that impulsivity of the individual degassing events is clearly visible as the vertical part in the cumulative energy plots.
Spectrograms for two of the impulsive pressure events: 1.2 kg/m^2 and 4 kg/m^2. The acoustic pulse associated with the initial m/s 2/C^2 energy radiated by each of the Augustine explosive activity at different volcanoes [Johnson, 2003]; for example, energy estimated from infrasonic traces recorded at Stromboli [Ripepe and Marchetti, 2002] present a value of 1 \times 10^8 Joule. Acoustic energies estimated for vigorous degassing activity at Sakurajima Volcano [Garces et al., 1999] have a value of 4 \times 10^7 Joule. Although this value is comparable to energies estimated for Augustine, the corresponding acoustic waveforms have a significantly smaller peak excess pressure of 4 Pa at ~3 km from the vent; the Sakurajima infrasound is less intense but longer in duration.

4. Discussion

1.4 We have presented acoustic signals associated with the spectra for two of the impulsive pressure signals recorded at AUE in January 2006 (acoustic onsets: 11-Jan-06 13:44:55 UT and 13-Jan-06 20:22:15 UT; fft length: 1024 samples, 80% overlap). Black indicates the highest energies.

(e.g., Figures 3a, 3c, and 3d) lasting 20–150 s. These signals generally display large peak amplitudes (32–105 Pa); coda durations vary between 20 and 120 s, which may depend on how much the system was able to degas during the initial burst. The impulsive phase exhibits a higher frequency content with the dominant energy between 0.1 and 3 Hz; the coda waves have frequencies confined below 2 Hz (Figure 4). If we reduce the recorded pressures to 1 km, assuming an inverse pressure decrease with radial distance from the vent, the largest acoustic pulse has a pressure of 336 Pa. The formation of shock waves for explosions with such large excess pressures seems likely, but could not be confirmed due to the limited visual observations.

[13] The January 11 acoustic signal associated with the onset of the Augustine eruption sequence exhibits a strong impulsive initial compressional peak of 93 Pa (Figure 5); the discrete peak is followed by a low-amplitude coda that lasts only 20 s. We suggest that this simple pressure pulse represents the initial vent-opening blast, that is, the sudden uncooking of the volcano. For a common seismo-acoustic source located at the vent, the expected time delay between the seismic and acoustic arrivals at station AUE is ~8 s (assuming that seismic and acoustic signals travel the same distance of 3.2 km, a seismic velocity of 3000 m/s, and an atmospheric acoustic velocity of 340 m/s). We measured a time lag of 14.0 ± 0.5 s. This discrepancy between the expected and measured time delays cannot be explained by a joint seismo-acoustic source, but exhibits strong evidence for precursory seismicity occurring about 6 s prior to sound generation.

[15] In addition to acoustic peak amplitudes, the radiated elastic energy estimated from infrasonic pressure traces provides a useful parameter for comparison of eruptive activity at different volcanoes [Johnson, 2003]. The acoustic energy radiated by each of the Augustine explosive events can be approximated by assuming an isotropic radiation of a linear elastic wave propagating through a homogeneous atmosphere [Johnson and Aster, 2005] as:

\[ E_{\text{acoustic}} = \frac{2\pi r^2}{\rho_{\text{atmos}} c_{\text{atmos}}} \int \Delta P(t)^2 dt \]

We assume an atmospheric sound velocity \( c_{\text{atmos}} = 340 \text{ m/s} \) and an atmospheric density \( \rho_{\text{atmos}} = 1.2 \text{ kg/m}^3 \), and integrate over the entire duration of the acoustic pressure trace \( \Delta P(t) \) recorded at a source-receiver distance \( r = 3.2 \text{ km} \). The acoustic waveforms have been high-pass filtered (>0.1 Hz) using a 2-pole Butterworth filter before the energy calculation. Acoustic energies estimated for explosion events at Augustine range between 2 \times 10^8 and 4 \times 10^9 Joule (Table 1). These are relatively high values compared to acoustic energies calculated for other volcanoes [Johnson, 2003]; for example, energy estimated from acoustic traces recorded at Stromboli [Ripepe and Marchetti, 2002] present a value of 1 \times 10^8 Joule. Acoustic energies estimated for vigorous degassing activity at Sakurajima Volcano [Garces et al., 1999] have a value of 4 \times 10^7 Joule. Although this value is comparable to energies estimated for Augustine, the corresponding acoustic waveforms have a significantly smaller peak excess pressure of 4 Pa at ~3 km from the vent; the Sakurajima infrasound is less intense but longer in duration.

**Figure 4.** The acoustic pulse associated with the initial vent-clearing event (acoustic onsets: 11-Jan-06 13:44:55 UT), recorded at AUE (acoustic and seismic) and 3 AUL broadband components (vertical = BHZ, east-west = BHE, north-south = BHN). The expected and measured time differences between seismic and acoustic arrivals at AUE, 8 and 14 s respectively, are marked in light grey. The impulsive acoustic onset does not correspond to the onset of the seismic signal, but is associated with a later part of the seismic waveform. Note that the seismic onset recorded at AUL is too small on the larger amplitude scale to be visible; the inset shows a 2.5 s close-up of the individually normalized seismic traces.
We observed a dramatic difference in character between emergent and impulsive events. The continuous nature of the emergent events reflects a non-impulsive extended release of the pyroclast-gas mixture that may be attributed to a combination of factors such as high magma viscosity, impediments at the vent and variable depths of fragmentation. The high-amplitude N-shaped phase of the impulsive events suggests an abrupt outward acceleration of gases and volcanic material from the vent, that is, the explosive start of a volcanic plume, which may be initiated by a large overpressure. The seismic and acoustic sources associated with the impulsive initial vent-opening explosion event were not conjoint; the sudden uncooking of the volcano and initiation of the plume was preceded by precursory seismic activity. The pre-explosion seismic energy may have been related to fracturing or movement of material within the over-pressurized sealed edifice prior to its arrival at the ground-air interface.

The acoustic signals recorded at Augustine have further demonstrated that microphones deployed on volcanoes provide a useful tool for eruption monitoring. The presence of large pressure pulses helps to distinguish between sub-surface seismicity and seismic events associated with explosive degassing from the vent. In contrast to seismic signals, impulsive acoustic waveforms give a direct measure of the onset of explosive volcanic plumes, which is especially helpful whenever visual observations are limited by remote settings or by cloud cover. The acoustic signal strength characterizes the impulsivity of the degassing source.

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References

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