Repeating coupled earthquakes at Shishaldin Volcano, Alaska

Jacqueline Caplan-Auerbach*, Tanja Petersen

Alaska Volcano Observatory, Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Dr., Fairbanks, AK 99775-7320, United States

Received 13 November 2003; accepted 20 January 2005

Abstract

Since it last erupted in 1999, Shishaldin Volcano, Aleutian Islands, Alaska, has produced hundreds to thousands of long-period (1–2 Hz; LP) earthquakes every day with no other sign of volcanic unrest. In 2002, the earthquakes also exhibited a short-period (4–7 Hz; SP) signal occurring between 3 and 15 s before the LP phase. Although the SP phase contains higher frequencies than the LP phase, its spectral content is still well below that expected of brittle failure events. The SP phase was never observed without the LP phase, although LP events continued to occur in the absence of the precursory signal. The two-phased events are termed “coupled events”, reflecting a triggered relationship between two discrete event types. Both phases are highly repetitive in time series, suggestive of stable, non-destructive sources. Waveform cross-correlation and spectral coherence are used to extract waveforms from the continuous record and determine precise P-wave arrivals for the SP phase. Although depths are poorly constrained, the SP phase is believed to lie at shallow (<4 km) depths just west of Shishaldin’s summit. The variable timing between the SP and LP arrivals indicates that the trigger mechanism between the phases itself moves at variable speeds. A model is proposed in which the SP phase results from fluid moving within the conduit, possibly around an obstruction and the LP phase results from the coalescence of a shallow gas bubble. The variable timing is attributed to changes in gas content within the conduit. The destruction of the conduit obstacle on November 21, 2002 resulted in the abrupt disappearance of the SP phase.

Published by Elsevier B.V.

Keywords: Shishaldin Volcano; volcano seismology; long-period earthquake

1. Introduction

Since late 1999, shortly after it produced a Subplinian eruption, Shishaldin Volcano, Unimak Island, Alaska (Fig. 1), has exhibited up to thousands of daily small long-period (LP) earthquakes. This level of seismicity is in stark contrast to the other 24 volcanoes monitored by the Alaska Volcano Observatory (AVO), which generally experience a few earthquakes per week (Dixon et al., 2003). While swarms of earthquakes are typical on volcanoes, the continuous nature of Shishaldin seismicity makes it unique among Alaskan volcanoes and unusual among
monitored volcanoes in general. Shishaldin’s behavior is also perplexing in that the elevated seismicity is apparently unassociated with other evidence of volcanic unrest such as thermal anomalies. Finally, this activity is notable for the extreme similarity evidenced among events over long time scales (Petersen et al., 2002).

Volcanic seismicity commonly heralds eruptive activity. While there is a great deal of variety in the type and duration of pre-eruptive seismicity, it is largely accepted that a high degree of seismicity on a volcano reflects the activation of internal eruption processes such as the rise of magma from depth, dike propagation, or pressure increase related to changes in gas flux (e.g. Klein et al., 1987; Lahr et al., 1994; McNutt, 2000; Chouet, 2003). LP earthquakes in particular are commonly seen as indicators of volcanic unrest, as they are believed to relate to the presence of fluids such as magma (Fischer et al., 1994; Lahr et al., 1994; Chouet, 1996). Thus, a continuously high level of LP activity is troubling, especially for an organization such as AVO which is responsible for eruption forecasting and hazard assessment.

In early 2002, the appearance of Shishaldin seismicity changed, with the addition of a precursory short-period (SP) phase to the LP events. We refer to this pair of earthquake phases as a "coupled" event and show that it is unlike other multi-phase earthquakes commonly presented in the volcano seismology literature. In this article we first give an overview of Shishaldin seismicity, and then explain how the coupled earthquakes differ from more common earthquake types such as LP or hybrid events. We describe the coupled events in detail, discussing event similarity, earthquake
location and the relationship between the signal’s two phases. Finally we propose a mechanism by which coupled events may be generated and discuss the implications for hazards monitoring at Shishaldin.

2. Geologic setting

Shishaldin Volcano is among the most active volcanoes in Alaska, with 29 confirmed eruptions in historic time (Miller et al., 1998; Nye et al., 2002). Its eruptions are composed primarily of basalt and basaltic andesite, although rare lavas with up to 64 wt.% silica have been identified (Fournelle and Marsh, 1991; Miller et al., 1998). The tallest volcano in the Aleutians, Shishaldin’s summit reaches 2857 m above sea level and glaciers and snowfields blanket its surface year-round. A puffing gas plume nearly always emanates from the volcano’s summit. Although the composition of the plume is unknown, observations have been made of sulfur deposits within the mouth of the conduit and a strong sulfur smell has been associated with gas puffs (P. Stelling, personal communication, 2003). This suggests that some portion of the plume results from magmatic gases.

Although most of Shishaldin’s eruptions have consisted of small ash and steam plumes, at least 11 Subplinian deposits have been identified in Holocene stratigraphy (Beget et al., 1998). The most recent eruption, in April–May 1999, consisted of both Strombolian bubble and ash bursts and a 16-km Subplinian eruption column. Thus, while the majority of its eruptive activity is small and local to the region, the fact that Shishaldin is capable of generating high and voluminous ash plumes confirms that it must be recognized as a hazardous volcano.

Unimak Island, the easternmost island in the Aleutian chain (Fig. 1) comprises 5 volcanoes, including Shishaldin. The two nearest population centers are False Pass, located ~60 km from Shishaldin on the island’s eastern coast, and Cold Bay, located on the Alaska Peninsula ~92 km from Shishaldin. Unfortunately, Shishaldin cannot be seen from False Pass because the nearer volcanoes Round Top and Isanotski block the view. AVO is therefore dependent on local pilots or observers in Cold Bay for visual descriptions of the volcano and its activity. Overall, however, visual observations are minimal and AVO relies heavily on telemetered seismic data and satellite imagery for volcanic monitoring. This lack of visual observation makes it difficult to examine possible correlations between Shishaldin seismicity and factors such as precipitation, or the strength of the ubiquitous gas plume at the volcano’s summit.

3. Seismic network and history

In 1997, AVO installed a 6-station seismic network near Shishaldin, and in 1998 a network was installed on Westdahl volcano west of Shishaldin (Fig. 1). Five of the Shishaldin stations have short period Mark Products L-4 vertical seismometers with 1 Hz natural frequency. Station SSLS has a 3-component Mark Products L-22 seismometer with 2 Hz natural frequency. A Setra 239 pressure sensor was co-located with station SSLN on the volcano’s north flank, but stopped functioning in late 1999, and was replaced in 2003 by a Chaparral Model 2 microphone. Data from all instruments are telemetered to the nearby towns of Cold Bay and King Cove and then to AVO over analog telephone lines. Once in Fairbanks the data are digitized at 100 Hz with 12-bit resolution.

While the 1999 eruption proved that the network is effective for volcanic monitoring (Moran et al., 2002; Nye et al., 2002; Thompson et al., 2002; Caplan-Auerbach and McNutt, 2003), the large distance between the outer stations and Shishaldin’s summit (14–19 km; Fig. 1) makes location of small events extremely difficult. Furthermore, station ISNN suffers from a poor telemetry link, resulting in large data gaps from that station. Finally, LP and coupled earthquakes do not exhibit clear S-waves. Thus for earthquake locating we can typically use a maximum of 5 P-waves, with 4 phases the more common situation. Consequently, conventional locations of Shishaldin earthquakes are not always possible, although preliminary locations place them beneath the summit at shallow (0–3 km) depths (Dixon et al., 2003).

The seismicity commonly observed in volcanic regions can be described using an event classification scheme such as those developed by Minakami (1960) and Lahr et al. (1994) based on the present understanding of source mechanisms. The volcanic event types most commonly observed include volcanotectonic (VT) earthquakes, LP events and hybrids.
Volcano tectonic (VT) events are high-frequency earthquakes, occurring within or beneath the volcanic edifice. They represent the brittle failure of rocks due to stress changes within the volcano. Although the source of the stress may be volcanic in nature, such as magmatic activity or transport of volatiles to the surface (Lahr et al., 1994; Moran, 2003), VT earthquakes are otherwise indistinguishable from tectonic earthquakes. VT events show characteristics similar to common double-couple tectonic earthquakes, e.g. they have clear P- and S-phases with significant energy at frequencies >5 Hz and a variety of first-motions (Lahr et al., 1994). In March 1999, a shallow M$_{L}$ 5.2 earthquake occurred 16 km to the west of Shishaldin, followed by a several-month long aftershock sequence of VT events (Moran et al., 2002). Since then, only a few VT earthquakes have been located at Shishaldin, almost exclusively restricted to the area 10–15 km west of the summit.

LP events are low-frequency (1–2 Hz) earthquakes commonly associated with fluids moving in volcanic conduits or cracks (Chouet, 1988, 1996; Julian, 1994; Neuberg et al., 1998). They are characterized by emergent onsets due to a gradual increase of ground shaking caused by fluid-driven oscillation (Lahr et al., 1994). The S-waves of LP events are not distinct and their codas are extended. At Shishaldin, the vast majority of earthquakes are LP events. The omnipresent steam plume and steam puffs suggest that these events might be related to degassing processes, however, the underlying source mechanisms are still poorly understood.

A third type of earthquake, termed the hybrid, is related to both VT and LP events. Hybrid earthquakes typically begin with an impulsive, short-period onset followed by an LP-like coda. Initial descriptions of hybrid events noted that, like VT events they commonly exhibit a variety of first motions and clear S-phases (Lahr et al., 1994; White et al., 1998). However, other researchers have discarded this requirement and note that hybrids are part of a continuum of events that include LPs (Neuberg et al., 2000). Lahr et al. (1994) suggest that hybrids result from brittle failure on a plane intersecting a fluid body, thereby combining the source mechanism for both VT and LP events. Earthquakes of this sort have been observed at a number of volcanoes, including Deception Island (Ibanez et al., 2003), Galeras (Gil Cruz and Chouet, 1997), Montserrat (Neuberg et al., 1998; White et al., 1998), and Redoubt (Lahr et al., 1994).

Prior to March 2002, Shishaldin activity was composed almost exclusively of LP events. On March 13, however, a new type of earthquake was identified, and became the predominant event type until November. These earthquakes begin with a short-period (SP) phase, followed by what appears to be a normal LP event. Subsequent investigation of earlier records indicated that these events were present prior to March 13 but in small numbers and at weak amplitudes. We refer to these events as coupled because, like hybrid earthquakes, they involve two discrete phases. However, for a number of reasons, we believe that the source process commonly invoked for hybrid events, brittle failure near a fluid filled crack, is unlikely for Shishaldin events. First of all, the SP phase of Shishaldin coupled earthquakes is strongly bandlimited between 4 and 7 Hz, which is quite low for local brittle failure. There are also few identifiable S-phases for either the SP or LP phases. As we will show, the SP portion of Shishaldin events is highly repetitive for prolonged time periods (days to weeks). It is unlikely that repeating brittle failure event could retain such similarity in waveform over such a long time, since with time the source process would alter conditions at the source region. Because the SP phases are generally small, and somewhat emergent, first motions are difficult to constrain. Unlike traditional hybrid events, the timing between SP and LP phases in Shishaldin coupled earthquakes is highly variable, as will be described later in this article. Finally, the LP phase bears significant similarity to “normal” LP events, suggesting that it is triggered by the SP phase and is not simply a later phase of the same earthquake. Consequently we call these events “coupled earthquakes” and propose a different mechanism for their formation.

4. Coupled events observed elsewhere

Because some Shishaldin coupled events bear similarity to hybrid earthquakes recorded elsewhere, it is non-trivial to determine how common such events are at other volcanoes. However, events that appear similar in time series to Shishaldin coupled events have been noted on a handful of other volcanoes.
(Galeras, Gil Cruz and Chouet, 1997; Stromboli, J. Lees, personal communication, 2002; Deception Island, Ibanez et al., 2003; Koryakski, Gordeev and Senyukov, 2003; Popocatépetl, R. White, personal communication, 2003). Signals called “secondary events” were identified as precursory to LP events at Redoubt volcano, but were only visible on a single station and thus could not be thoroughly examined (Stephens and Chouet, 2001). Precursory signals identified at Koryakski volcano, Kamchatka were interpreted by Gordeev and Senyukov (2003) to be related to magma injection into cracks. Gil Cruz and Chouet (1997) note their occurrence on Galeras volcano in 1991 and suggest a source mechanism involving two discrete cracks and a rising gas bubble. Ibanez et al. (2003) were able to determine that the short and long-period phases of these earthquakes have different locations and attribute their source to brittle failure on faults lubricated by fluids. Thus, although they are not common features, events similar to Shishaldin coupled events have been identified at a number of volcanoes. However, Shishaldin events appear to be unique in the variable timing observed between the SP and LP phases, and the spectral content of the SP phase is generally lower than that observed elsewhere. Consequently, we propose a slightly modified mechanism for the events described here.

5. Identification and extraction of repeating earthquakes

A preliminary examination of Shishaldin seismicity shows that many of its earthquakes, both LP and coupled, appear similar in time series (Petersen et al., 2002). Because these events are small, only a low percentage trigger the data acquisition system using the EARTHWORM triggering algorithms Carlstatrig and Carsubtrig (Dixon et al., 2003). Consequently, most events are not automatically segmented for further analysis. To examine a larger subset of coupled events we took advantage of the fact that the earthquakes are repetitive and developed a method by which similar events could be extracted from the continuous record (Fig. 2). In this algorithm, a “reference event” is selected against which other earthquakes will be compared. The reference event is selected somewhat arbitrarily, with the only criteria being a good signal-to-noise ratio and no overlap with other events. The continuous record is divided into

![Fig. 2. Cross-correlation technique used to extract repeating events from the continuous record. An SP reference event, shown in red, is cross-correlated with segments of the continuous record and aligned at the point of maximum correlation. The spectral coherence is then calculated in the frequency band of the reference event (4–7 Hz for SP events) and events with coherence estimates exceeding 0.9 are segmented from the continuous data. Note that the first event shown in the top panel was not sufficiently similar to the reference event to be considered for further analysis.]
segments of length equal to that of the reference event, and each segment is cross-correlated with the reference event. The maximum cross-correlation value yields the lag position at which the two signals correlate most strongly, and a data segment beginning at that time is selected from the continuous record for coherence testing. The spectral coherence between this data segment and the reference event is calculated and the mean coherence in a specified frequency band is examined. All data segments with mean coherence exceeding a threshold value (typically 0.9 for the SP phase of coupled events) are selected as part of an event group. The initial selection of events was made using station SSLN, the station on which Shishaldin events typically exhibit the highest signal-to-noise ratio, although we were successful in performing the same task using other stations. Once the repeating events are selected, a 30-s window around each event is extracted for all stations in the network, and the data are thereby segmented. This method allows us to select a sequence of repeating events from the continuous record that are too small to trigger the data acquisition system. This method is similar to the one used by Stephens and Chouet (2001) in their analysis of LP seismicity at Redoubt volcano. As with all other methods used to count events at Shishaldin (Petersen et al., 2002), this method only selects a small subset of earthquakes. However, this subset was sufficient to examine the coupled events, their locations and their temporal behavior. Petersen et al. (2002) performed a similar analysis for the LP events.

Each reference event was used for a time period ranging from days to weeks, until no events were found that fit the coherence criteria for selection. When the number of daily extracted events dropped to zero for more than 2 days we selected another reference event and tested an overlapping time period. In total, we were able to extract >7000 coupled events between March 13 and November 21, 2002, using the SP phase and eight reference events (Table 1). We note that although we have used eight reference events, this does not reflect eight distinct event families, but rather a continuously evolving source process.

It is important to note that the extraction algorithm could be simplified by selecting events with high correlation coefficients rather than spectral coherencies, since coherence requires conversion to the frequency domain. We chose to use the spectral coherence for two reasons. First of all, the SP phase of the coupled events typically has much smaller amplitude than the LP phase. Consequently, we often find the highest correlation coefficients when earthquakes are aligned with their LP rather than SP portions in phase. Secondly, because the signals are fairly monochromatic, they may be misaligned by a unit number of periods, yet still have a high correlation coefficient.

6. How similar are coupled events?

The coupled events discussed in this work were selected because their SP phases were determined to be similar to a reference event. Thus, each SP event is known to have a coherence estimate of 0.9 relative to one specific SP earthquake. This does not provide information about how similar all SP phases in the cluster are to one another, and how they compare to events extracted using other reference events. Nor does it provide information on the repeatability of the LP phases of coupled events. Thus, we sought a means by which the entire data set, or a generalized subset thereof, could be examined.

As previously noted, Shishaldin coupled events do not typically trigger the data acquisition system. Thus, in order to investigate all of the coupled events at Shishaldin, not just those that meet specific similarity criteria, we needed to segment the data in a manner.

---

### Table 1

<table>
<thead>
<tr>
<th>Event group</th>
<th>Start date</th>
<th>End date</th>
<th>Number of events extracted by SP phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>March 3</td>
<td>April 27</td>
<td>1442</td>
</tr>
<tr>
<td>2</td>
<td>April 27</td>
<td>June 19</td>
<td>1258</td>
</tr>
<tr>
<td>3</td>
<td>June 14</td>
<td>July 25</td>
<td>1773</td>
</tr>
<tr>
<td>4</td>
<td>July 14</td>
<td>July 21</td>
<td>426</td>
</tr>
<tr>
<td>5</td>
<td>July 22</td>
<td>August 19</td>
<td>380</td>
</tr>
<tr>
<td>6</td>
<td>August 24</td>
<td>September 16</td>
<td>1151</td>
</tr>
<tr>
<td>7</td>
<td>September 7</td>
<td>October 9</td>
<td>202</td>
</tr>
<tr>
<td>8</td>
<td>September 28</td>
<td>November 21</td>
<td>943</td>
</tr>
</tbody>
</table>

Each period reflects a time in which a single reference event was dominant. Time periods were considered to end if two days passed in which no events similar to the reference event were found. Note that there is some overlap in the time periods, reflecting times in which some variation in event appearance was observed.
that would identify all earthquakes rather than those that meet similarity criteria. To this end we first filtered the data between 3 and 8 Hz, to enhance the SP phase of coupled events. A new short-term-average/long-term-average (STA/LTA) ratio (STA period=0.2 s, LTA period=5 s, ratio=4) was used on the filtered data to select all events in that frequency band occurring on a given day. With this algorithm we were able to identify hundreds of SP events per day, regardless of their similarity. Because the sheer quantity of events made it impossible to perform this function on all of the data, we selected a subset of days for which signal-to-noise was strong and identified all events for those days. We chose 1 day for each time period covered by a reference event, with the exception of the first time period, for which we examined 2 days, and period 4 which overlaps both periods 3 and 5 (Table 2). This gave us a subset of data with which we could examine the similarity between events from different time periods as well as events from within the same time period.

Because spurious signals may be selected using the STA/LTA algorithm, we examined all of the segmented events and manually deleted any events that were obviously not SP phases of coupled events. Events that were identified by the algorithm included calibration pulses, electronic spikes due to telemetry problems and regional earthquakes, all of which were removed from the data subset. Additionally, we removed earthquakes that overlapped the coda of previous events. Of 2847 events of all types initially extracted, 1400 coupled events were selected for further analysis.

One of the goals of this analysis was to evaluate our decision to use separate SP reference events for each of eight time periods (Table 1). To that end we calculated the spectral coherence between each reference event and all 1400 events in the data subset. In general, only days in the time period originally assigned to a reference event contained earthquakes selected by that event. In other words, events on May 11, a day initially assigned to time period 2, were selected only when reference event 2 was used. No events occurring on May 11 were selected using any other reference event. Events in time periods 6 and 7 were found to be mostly interchangeable, suggesting that the two time periods comprise similar event types. The only other interesting exception is that reference event 2 was found to be highly similar (coherence>0.9) to 15 events that occurred during first time period. In contrast, no earthquakes on the day selected from time period 2 were extracted using reference event 1. This suggests that there may have been two distinct SP sources in the initial time period, but that the second type became dominant by late April. Overall, these results (Table 2) confirm that the decision to use different reference events in each time period was robust.

Next we examined all earthquakes in the data subset to investigate their similarity. To that end we calculated the coherency between the SP phases of all 1400 events in the data subset. To ensure that we are looking at the similarity of the SP phase only, we calculated the mean coherence in the frequency range of the SP phase, between 4 and 7 Hz. The total results and mean coherence values for each event are shown in Fig. 3a. The matrix diagonal (running from the

Table 2
Number of events extracted on selected days using eight different reference events

<table>
<thead>
<tr>
<th>Date</th>
<th>Time period</th>
<th>Number of coupled events (STA/LTA)</th>
<th>Ref event 1</th>
<th>Ref event 2</th>
<th>Ref event 3</th>
<th>Ref event 4</th>
<th>Ref event 5</th>
<th>Ref event 6</th>
<th>Ref event 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 26</td>
<td>1</td>
<td>234</td>
<td>59</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>March 30</td>
<td>1</td>
<td>166</td>
<td>55</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>May 11</td>
<td>2</td>
<td>142</td>
<td>0</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>July 10</td>
<td>3</td>
<td>265</td>
<td>0</td>
<td>0</td>
<td>56</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>July 25</td>
<td>5</td>
<td>169</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>August 29</td>
<td>6</td>
<td>311</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>75</td>
<td>93</td>
<td>0</td>
</tr>
<tr>
<td>September 23</td>
<td>7</td>
<td>134</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>October 24</td>
<td>8</td>
<td>244</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>14</td>
</tr>
</tbody>
</table>

In general, events were extracted using only the reference event associated with that day’s event group. In some instances, however, events on a given day were found to be similar to multiple reference events. This suggests either that there were multiple event types occurring simultaneously, or that events were similar to several reference events, reflecting a gradually evolving source.
Fig. 3. Estimated spectral coherencies for (a) the SP phase and (b) the LP phase of 1400 coupled earthquakes occurring over the span of the time period of this study (March–November 2002). For the SP phase, the coherence was calculated for each event pair in the frequency band between 4 and 7 Hz for the 5 s around the P-wave. A frequency band of 0.5–3 Hz was used to estimate the spectral coherence for the first 5 s of the LP phase. The scale for spectral coherence is shown to the right. Values lying on the diagonals represent the auto-coherence between an event and itself and are everywhere equal to 1. Points close to the diagonal represent events that occur closely spaced in time while those farther from the diagonal are separated by longer time periods. The days from which data were extracted are shown on the top of the figure. While each event exhibits a range of coherence values, the overall values are high, typically exceeding 0.7 for SP phases and 0.6 for LP phases, indicating a high degree of similarity over 9 months. Also evident is the fact that for the SP phase, certain time periods exhibit long-term similarity while others change more rapidly. Events occurring between March and May are highly similar to one another, as are events occurring between August and October. This suggests a minor but long-term change in the SP source process. In contrast, the LP phase shows little temporal evolution.
lower left to upper right in Fig. 3a) shows the auto-
coherence for an event (the spectral coherence with
that event and itself) and is equal to 1. Values close to
the diagonal represent events that are closely spaced
in time, while values plotted farther from the diagonal
represent the coherence between events spanning
longer time scales. In all cases, coherence values are
relatively high (0.7–0.9; Fig. 3a), with highest values
clustering near the diagonal. This indicates that while
all SP events are fairly similar, events are more likely
to be similar if they occur over a short time scale when
source conditions have not changed significantly.
Furthermore, events that occurred between March
and May have high coherence values relative to one
another, as do events occurring between August and
October. There is a strong decrease in coherence when
events in the former group are compared with events
in the latter (Fig. 3a). In contrast, events extracted in
July bear strong similarity only to each other. This
indicates that there was a slight but significant change
in the SP phase between May and August 2002.

A similar test was performed for the LP phase of
the 1400 coupled events included in the SP analysis.
As with the SP phase, the LP portions of coupled
events were cross-correlated with one another and the
coherencies calculated for a 5-s window (Fig. 3b).
This analysis shows that overall, LP phases have
slightly lower correlation coefficients than the SP
phases for the same events, averaging 0.6–0.8.
Furthermore, LP phases do not show the same
temporal trends evident in the SP phase analysis.
This suggests that LP phases do not change signifi-
cantly over long time scales and may have a more
stable source mechanism.

7. Coupled event delay times

A benefit of identifying groups of events by
extracting similar events is that the events are
segmented such that the earthquakes are aligned in
time series. This method of viewing the activity
promotes identification and timing of different phases.
Examples of such a plot for a single day of coupled
earthquakes are shown in Fig. 4. This perspective
clearly shows that when the SP phases are aligned in
time series, the arrival times of the LP phases occur
anywhere from 3 to 15 s after the SP phase (Fig. 4). In
this article, the time period between the SP and LP
phases will be called the “SP–LP delay time”, or
simply the “delay time”. At times the delay time is
found to vary dramatically over short time scales (Fig.
4a and b) while at other times the delay time is
relatively consistent (Fig. 4c and d). As previously
noted, when delay times change rapidly, there does
not appear to be a systematic timing change. In some
instances a change in delay time is followed by a long
sequence of events while in other cases, only a few
events occur before delay times change yet again. The
observed changes in delay time are visible at all
stations, suggesting that the delay results from a
source effect rather than one associated with site or
path. Finally, more distant stations exhibit slightly
longer delay times (Fig. 4). This timing difference
indicates that the two phases have different source
locations or different phase velocities.

To estimate delay times for all events we need to
identify the start of both phases. The SP phase onset is
easily determined as it is identified during extraction of
similar events. To determine the beginning of the LP
phase, we filtered the data between 0.5 and 4 Hz and
used an STA/LTA algorithm. Because the LP phase
often begins in the coda of the precursory SP phase, and
because the onset of LP activity is emergent, we
estimate a 2-s uncertainty in the actual delay time.
Although the actual delay times are approximate, the
general trend, that of wide variability at some times and
consistent delay times at others, is robust.

When delay time is plotted for the time period of the
study (March–November 2002; Fig. 5) we see that
there are time periods (e.g. late March) with highly
variable delay times, while at other times (e.g. late July,
November) the two phases occur at predictable
intervals. Furthermore, there are general trends in the
data: delay times are short in April and May but longer
between June and September. This suggests that the
mechanism acting between the two phases not only
changes on short time scales but occasionally stabilizes
at the maximum or minimum observed values.

To further investigate SP–LP delay times, we
plotted delay time against several parameters for
Shishaldin coupled events (Fig. 6). We found no
correlation between delay time and interevent time
(Fig. 6a). There is only a weak correlation between the
maximum amplitude of the SP phase and the delay
time (Fig. 6b); high amplitude SP phases correlate
with short delay times. However, at small delay times the apparent maximum amplitude for SP events may be influenced by overlapping signal from the larger LP phase resulting in larger apparent amplitudes. Although there appears to be a slight decrease in event count with the time of day (Fig. 6c), this may be due to an increase in noise resulting from afternoon winds (occurring toward the end of the UTC day). Spectral analysis of event occurrence times shows no obvious peaks, thereby ruling out tidal or diurnal effects. Coupled events occurred throughout the time period from March to November 2002, suggesting that there is no correlation between seismic activity and precipitation. However, since there are no meteorological stations on Unimak Island, this lack of correlation cannot be positively confirmed.

8. Relationship between LP phases and LP events

The LP phase of the coupled event bears strong similarity to the LP events that occurred prior to March 13 and after November 21. The possibility therefore exists that the LP phase visible within coupled events is the same as other LP events, with the only difference being the SP trigger. Thus, to better understand the coupled events, we investigate the relationship between Shishaldin LPs and the LP phase of coupled earthquakes. We can examine the LP signals by comparing the time series of a “typical” LP event (that is to say, unassociated with an SP precursor) and the LP phase of a coupled event (Fig. 7a). In this format it is evident that the two events are highly similar from the onset time at 20 s until approximately 37 s into the file. This similarity is visible at all stations, again suggesting that the similarity is due to source rather than path or site effects. When the data are bandpass-filtered to enhance SP energy (Fig. 7b) it is clear that only one of the LP events has an associated SP precursor. These data suggest that the LP phase of Shishaldin coupled events shares a common source mechanism and location with other Shishaldin LPs; the only difference between the two events is the presence of the precursory SP phase for the coupled events.

As a final check as to the relationship between LP and coupled events, we scanned through several days...
Fig. 6. Representations of the SP–LP delay against various parameters associated with the coupled events. (a) Interevent time for repeating coupled events plotted against delay time. (b) Maximum amplitude of the SP phase versus delay time. (c) Number of events that occurred during each hour of the day. No strong correlation exists between delay time and interevent time. There are slightly fewer events towards the end of the UTC day, corresponding to late afternoon Alaska time. This probably reflects an increase in background noise due to wind rather than an actual decrease in event numbers. There is a very weak correlation between the amplitude of the SP phase and the delay time; high amplitude SP phases occur for short delay times only.
of data to estimate the ratio of “normal” LP events to coupled events. Identifying LP events that are not associated with SP precursors is difficult because SP phases are small and may easily be masked by noise, giving the event the appearance of a standard LP. However, our estimated counts suggest that during the time frame of this study (March–November 2002), there were roughly twice as many coupled events as LPs. In contrast, on January 3, 2002, 183 LP events were counted, compared to only 38 coupled events. This activity occurred before the coupled events were identified as a distinct event type. Intriguingly, we note that when coupled events were dominant, the LP phase of the coupled events was significantly larger than plain LPs. Similarly, on January 3, when LP events were among the largest noted at Shishaldin, the amplitude of the SP phase of coupled events was so small that they were not identified except in retrospect. Thus there appears to be a trade-off in energy content; the bulk of the energy released by Shishaldin’s seismicity resides in one event type at a time.

9. Earthquake locations

Shishaldin earthquakes are extremely difficult to locate due to their small magnitude and the station geometry described above. Initial locations of the largest coupled and LP events place their hypocenters at 0–3 km directly beneath Shishaldin’s summit (Dixon et al., 2003), but hypocenters for the majority of events cannot be calculated by traditional means. We made use of the similarity of Shishaldin activity to estimate locations of the smaller earthquakes.

Locating the SP phase of the coupled events first required a means to enhance the first arrivals. To that end, we began by stacking all of the events selected with a single reference event. In some cases this consisted of events spanning several weeks while for other reference events we found similar events occurring for only a few days (Table 1). Following the removal of noisy traces, events for each group were aligned by cross-correlation and stacked at each station. P-wave arrival times were picked for the stacks, and the events were located using HYPOELLIPSE (Lahr, 1999). The velocity model used for Shishaldin is composed of seven constant-velocity layers and was originally derived for Pavlof volcano (McNutt and Jacob, 1986). We were unable to identify P-wave arrivals at station BRPK (Fig. 1), even after stacking several hundred earthquakes, so that station was not used in the locations. As previously mentioned, station ISNN suffers from a poor telemetry link, so for event group 5 (Table 1) we found no usable traces at that station.
Hypocentral locations for the stacked events are shown in Fig. 8. Although the events are clearest at station SSLN they occur just west of the summit, midway between stations SSLN and SSLS. Depths are very poorly constrained due to (a) the lack of reliable S-phases and (b) the low number of stations recording the activity, but the best fit locations are at shallow (<4 km below the summit) depths. Thus, although we do not know exact hypocentral depths, we take 4 km to be the maximum likely depth for the source of the SP phase. Note that the apparent “airquakes” visible in Fig. 8 (earthquakes whose depths are above regional topography) are a consequence of the location algorithm’s assumption of flat topography. These events are obviously poorly located but indicative of shallow depths.

Although the small amplitude of Shishaldin events makes it impossible to pick reliable P-waves for individual events, we were able to estimate arrival times by cross-correlating each waveform with the stacked events. The number of lags at maximum correlation yields the number of samples by which each event is offset relative to the stack and allows us to pick an arrival time to within 0.01 s. Picks were weighted according to the correlation coefficient, such that events with correlations exceeding 0.8 were given full weight, and those with correlations of <0.4 were not used in the location. Of the ~7000 earthquakes selected for this study, 1400 were located with HYPOELLIPSE quality factors of A or B, indicating 68% confidence levels for horizontal and vertical locations of <2.67 km (Lahr, 1999). Not surprisingly, those locations cluster tightly in the same region as the stacked events, on the west flank of Shishaldin, near the summit. As with the stacked events, depths are poorly constrained between 0 and 4 km. In all cases, however, the events appear to be shallow and within the Shishaldin edifice. While these hypocenters may be considered suspect due to the low number of stations, we note that in the vast majority of cases, the best correlations for all stations were found with offsets of less than 2 samples (0.02 s), requiring that all of the events have their source within ~100 m of each other. No temporal trends in earthquake locations are evident.

We attempted the same stacking analysis on the LP phase of the coupled earthquakes but were unsuccessful in determining reliable hypocenters. Because the LP phase occurs after the SP phase, first arrivals in LP data were often difficult to identify. Furthermore,
even in stacked data, the onset of the event was too emergent to accurately time first arrivals. Because of the low-frequency nature of the event, a half-wavelength uncertainty in first arrivals corresponds to a long time interval (~0.5 s) and consequently a large degree of location uncertainty. However, there is reason to believe that, like the SP phase, the LP phase of the coupled event has its source within Shishaldin’s edifice. Firstly, delay times are slightly offset between stations; an event with a 5-s delay time at station SSLN (6.3 km from the vent) exhibits just over 5–6 s of delay at SSLW (10 km from the vent) and 7–8 s of delay at ISTK (17.1 km from the vent). This allows us to conclude that the SP and LP sources have discrete locations, since delay times would be consistent across the network for co-located phases. The relatively small move-out further suggests that the two phases have sources near one another, or at least within the immediate vicinity of Shishaldin. If one source region lay significantly farther we would expect to see larger move-out at the more distant stations. Finally, conventional location of pure LP events places them at shallow depths beneath the summit (Dixon et al., 2003) and stacking analysis of pure LP events yield similar hypocenters (Petersen et al., 2004). If LP phases share a common source with LP events, then they would also be located in the shallow edifice.

10. A proposed model for Shishaldin coupled earthquakes

Several parameters must be considered when proposing a model for Shishaldin coupled earthquakes. The first is the coupled nature of the event; each SP phase is followed by an LP phase, and no SP events have been identified without a succeeding LP phase. In contrast, LP events occur without the SP precursor, and waveforms for some standard LPs are virtually identical to the LP phase of Shishaldin coupled events. Secondly, the repetitive nature of both the SP and LP phases suggests that each represents a stationary, non-destructive source process, although there is more variability in the appearance of the LP phases (Fig. 3b; Petersen et al., 2002). Nonetheless, events with variable SP–LP delay times have been identified for which both the SP and LP phases are highly similar (Fig. 9). Thus, if both source regions are fixed, then the variable timing between the two phases must be caused by variations in the mechanism that relates the two, i.e. the trigger mechanism. Next, the prolonged nature of the SP–LP delays, between 3 and 15 s, requires a trigger mechanism that can change speed by a factor of 5. And finally, since both source regions are believed to lie within the Shishaldin edifice, the trigger mechanism cannot travel more than a few kilometers over the delay time, and
therefore must move at slow speeds (<1 km/s). In fact, if we take the maximum depth of the SP phase to be 4 km below the summit (the maximum depth calculated for hypocentral locations), and assume that the LP phase is shallower, we can place constraints on the velocity of the triggering mechanism. The approximate range in delay time of 3–15 s for 4 km spacing yields a velocity range of approximately 270–1333 m/s. If the SP phase has a shallower source, or the LP source is located at greater depth, then these values would be considerably lower.

We believe that both the SP and LP phases of Shishaldin coupled events result from the presence of fluids within the volcano. This is consistent with the low frequency of these signals as well as the repeatability of the source. Furthermore, the plume at Shishaldin’s summit confirms that gas is constantly escaping the volcano, although the relative contributions of magmatic and meteoric gas are unknown. While no correlation has been confirmed between seismicity and the puffing steam plume, the observed timing between successive gas puffs (1–3 min) is similar to the timing between LP events recorded by the seismic network. Furthermore, the fact that the plume comes in “puffs” indicates that gas is released in discrete bursts. Finally, the installation of a more sensitive pressure sensor in 2003 allowed us to correlate LP events at Shishaldin with infrasonic signals (Petersen et al., 2004). Although a detailed investigation of this relationship is beyond the scope of this article, this correlation encourages us to assume a shallow, gas-related source for Shishaldin LPs and the LP phase of coupled events. Consequently, all the models we consider are based upon a volcano with two fluid-based sources.

There are many means by which fluids, and gas in particular, may generate seismic signals. One involves the sudden coalescence of foam into a single gas slug. This mechanism has been observed in laboratory experiments (Jaupart and Vergniolle, 1988, 1989) and has been invoked as a source of LP seismicity (Ripepe and Gordeev, 1999). When the slug reaches the top of the fluid it oscillates prior to bursting, inducing seismic and infrasonic signals (Vergniolle and Brandeis, 1994, 1996; Gil Cruz and Chouet, 1997; Vergniolle et al., 2004). Alternatively, LP events could be due to explosions resulting from magma–water, or fuel–coolant, interactions (Wohletz, 1986, 2002; Buttn and Zimanowski, 1998). An additional means by which fluid may generate seismic signals is by promoting oscillation of a crack or reservoir (Chouet, 1985, 1988; Julian, 1994; Garces, 1997). Conduit vibration may also be induced by choked flow at obstructions (Julian, 1994; Morrissey and Chouet, 1997) or by turbulent flow (Hellweg, 2000). Finally, fluid transfer through volcanic conduits has been invoked to explain LP events and tremor at a number of volcanoes, including Kilauea (Aki et al., 1977; Almendros et al., 2001), Lascar (Hellweg, 2000) and Sakurajima (Honda and Yomogida, 1993).

We first considered a model in which gas bubbles coalesce into a slug at a deep boundary and rise under their own buoyancy through magma or hydrothermal fluid. The SP phase of the coupled event is produced when the bubbles coalesce at depth. At some point as it rises through the conduit, the slug enters a second fluid body, perhaps a magma reservoir or crack, initiating the LP signal. This signal may result from the vibration of the reservoir walls or from the oscillation of the bubble itself. Thus the trigger event between the two phases of the coupled earthquake is a mechanical one, the rising of the slug itself. In this model we hypothesize that variations in SP–LP delay time result from changes in the rise speed of slugs at depth due to slug radius or fluid density and viscosity.

There are several reasons to immediately discount such a model. If the SP phase is both the trigger and the source for the LP phase, then the LP events cannot occur without the precursor. Yet the LP signals are observed to occur before, coincident with and after the time period in which coupled events were dominant. Thus it is more likely that the two phases have independent sources, but that the LP phase can be triggered into activity by the SP phase. Secondly, even for large slugs in dense fluid, the rise velocity is only a few m/s. For coupled events in which the LP phase follows immediately after the SP phase, this would require the SP and LP reservoirs to be within a few tens of meters of each other. It seems to be highly unlikely that two discrete reservoirs could coexist at such proximity for months without merging. Secondly, bubbles coalescing in a reservoir tend to form a slug which fills the conduit through which it rises; variable radii are not observed in laboratory models (Jaupart and Vergniolle, 1989; Vergniolle et al., 1996). Finally, we have shown that velocities for the
triggering mechanism are likely to be as high as several hundred m/s, a speed that is unattainable by a rising gas slug in magma.

In our preferred model, the trigger mechanism is seismic energy generated by the precursory SP event, rather than mechanical transport. In this model, the velocity of the trigger mechanism depends on the acoustic velocity of the material through which the wave propagates; in this case, the conduit fluid. We will show that small changes in gas content are sufficient to explain the observed variability in delay times.

We propose that coupled events initiate when a pressure transient within the conduit fluid creates the SP signal. Julian (1994) has shown that a small perturbation to steady-state flow within a conduit can result in transient seismic events. While many of the source mechanisms described above can also explain a signal such as the SP phase, a key parameter constraining the SP source is the fact that the similarity evident in SP waveforms is independent of the observed delay time. This rules out any source mechanism associated with conduit resonance, as crack wave velocities are dependent on the acoustic wave speed of the fluid (Chouet, 1988, 1996; Gil Cruz and Chouet, 1997). Because many fundamental parameters of the SP phase, such as source depth and regional material properties, remain unknown, an investigation of the SP power spectrum is beyond the scope of this study.

The same seismic energy recorded by the seismometers as the SP phase also travels within the volcano itself to a shallow portion of the conduit or reservoir where it triggers the LP source. There are two mechanisms that we considered for the LP source: magma–water interactions (Wohletz, 1986; Buttner and Zimanowski, 1998) and bubble coalescence (Jaupart and Vergniolle, 1988, 1989). In the former case, seismic waves impinging on a magma–water boundary collapse an insulating film layer at the boundary, causing superheated water to flash to steam. In the latter model, SP phase energy passes through a shallow layer of bubbles or foam (Fig. 10), causing the bubbles to decompress and rapidly coalesce into a bubble slug. The slug coalescence generates an LP signal and releases a pulse of gas. Both models can generate LP events with or without a triggering event: Superheated water can flash to steam without a trigger if it continues to heat past a critical temperature (Wohletz, 2002) and a foam layer that grows beyond a critical thickness will likewise collapse on its own (Jaupart and Vergniolle, 1988, 1989).

While both models are reasonable for Shishaldin, we prefer the bubble coalescence model. Magma–water interactions can generate instabilities at the magma surface, promoting magma break-up and an ensuing explosive eruption (Wohletz, 1986, 2002), which was not observed at Shishaldin in 2002. The ability of the volcano to continually supply water that is rapidly superheated is also questionable. Finally, there is no evidence of shallow magma in the Shishaldin conduit. In the case of the bubble coalescence model, there is a large supply of gas available in the form of volcanic and hydrothermal gases, and shallow magma is not required. In the models presented here, we assume the presence of magma but discuss the consequences for the case of other fluids.

To explain the variable SP–LP delay timing in this model, we seek a means by which the velocity of
seismic energy can be dramatically changed over short time periods. We invoke changes in fluid void fraction as a means of accelerating or decelerating the trigger mechanism. After Gil Cruz and Chouet (1997) we calculate $a_m$, the velocity of a pressure wave in a fluid according to

$$\frac{1}{a_m} = \frac{1}{a_l} + \sqrt{\frac{\rho_m \varepsilon_g}{\gamma_m P}}$$

(Hsieh and Plesset, 1961; Gil Cruz and Chouet, 1997). The fluid velocity is given by $a_l$, $P$ represents the pressure in the reservoir, and $\varepsilon_g$ is the void fraction of the fluid. $\rho_m$, the density of the gas-liquid mixture, depends on the void fraction $\varepsilon_g$ and liquid and gas densities $\rho_l$ and $\rho_g$ according to,

$$\rho_m = \varepsilon_g \rho_g + (1 - \varepsilon_g) \rho_l$$

Because these values have not been measured precisely at Shishaldin, we use commonly accepted values for gas and basalt and take $\rho_l$ to be 2700 kg/m$^3$ (Williams and Mc Birney, 1979) and $\rho_g$ to be 1 kg/m$^3$. The seismic velocity of the liquid magma is estimated as 2500 m/s. The isentropic coefficient of the mixture $\gamma_m$ depends on the specific heats of the gas and liquid as well as the mass ratio of gas to liquid. Because these values are not known specifically for Shishaldin we follow Gil Cruz and Chouet (1997) and take the value of $\gamma_m$ to be 1.0066.

Seismic velocity in low-viscosity fluid is strongly dependent on void fraction $\varepsilon_g$, with only a small amount of gas dropping the velocity far below that of either pure liquid or pure gas. In Fig. 11 we show seismic velocity for 2-phase fluids with a range of void fractions and reservoir pressures. Because the composition of the fluid within the Shishaldin conduit is unknown, we cannot precisely determine the pressure within the conduit. We can, however, estimate the regional pressure for the endmember cases of a conduit filled with magma ($\rho = 2700$ kg/m$^3$) and one filled with water ($\rho = 1000$ kg/m$^3$). We estimate the pressure as $P = \rho gh$ where $\rho$ is fluid density and is related to void fraction according to Eq. (2) above, $g$ is the acceleration due to gravity and $h$ is the depth within the conduit, between 0 and 4 km below the summit, according to the hypocentral

![Fig. 11. Velocity of seismic waves through gas-rich basaltic magma. Velocity is dependent on the fluid void fraction $\varepsilon_g$, as well as the ambient pressure within the fluid. Thin solid curves represent values calculated at pressures between 1 and 100 MPa, at 10 MPa intervals. The heavy solid line represents a pressure of 10 MPa for a magma-filled conduit. The heavy dashed line represents the same conduit filled with gas-rich water to a depth of 4 km, resulting in static pressure of ~4 MPa. White circles mark the gas velocities of 270 and 1300 m/s, the approximate maximum and minimum velocities estimated for the coupled event trigger mechanism.](image-url)
depths of the SP phase. These values give us an approximate pressure range of 5–100 MPa. All of these values decrease, of course, if we consider the presence of gas within the fluid. While we cannot determine the precise pressure within the conduit, these values allow us to investigate the effects of on seismic velocity at pressures that are reasonable for the conditions (Fig. 11).

The values shown in Fig. 11 confirm that only a small change in $e_g$ is required to explain the observed variability in delay time. For example, a magma at 10 MPa (heavy solid line in Fig. 11) experiences a 5-fold decrease in seismic velocity for a change in $e_g$ of 0.0004–0.042. More importantly, the predicted seismic velocities for this range of $e_g$ are between 270 and 1300 m/s, the precise range of velocities required to explain the observed delay times for an SP–LP source separation of 4 km. The results are similar for an identical water-filled conduit, with slightly lower values for $e_g$. At 4 km depth, pressure in a water-filled conduit is ~0.39 MPa (heavy dashed line in Fig. 11) and velocity is found to range between 270 and 1300 m/s for $e_g$ between 0 and 0.037 (Fig. 11).

The relationship described above, in which increased gas content results in increased SP–LP delay time, causes us to wonder if there might be a relationship between the interval between successive seismic events and the delay time. In the bubble coalescence model, long delay times indicate that more gas is available to generate bubble layers or foam, which would presumably result in more LP events. No correlation between interevent time and delay time was initially visible in our data (Fig. 8a). However, the interevent times presented in Fig. 8a are for SP phases only. To compare delay times to the total number of events, we selected 2 days and counted all earthquakes regardless of event type. On May 11, a day when delay times were low (3–5 s), indicating low gas content, we counted a total of 368 events. In contrast, we counted 957 earthquakes on July 25, when high delay times (10–12 s) suggest high gas content. This fact supports the bubble coalescence model for the LP phase.

As previously noted, when coupled earthquakes are the predominant event type, pure LP events appear to be of low amplitude. This model may indicate that the SP phase forces overpressurized bubbles to coalesce. Ripepe and Gordeev (1999) have shown that bubbles layers that coalesce freely do so when the hydrostatic pressure has diminished beyond a critical value. Bubbles that are forced to coalesce, however, exhibit larger overpressure and generate stronger seismic waves.

11. Demise of the coupled events

The last day on which the coupled earthquakes were dominant at Shishaldin was November 21, 2002. We find coupled events occurring until approximately 09:15 UTC, after which the events appear to be normal LP earthquakes. No other unusual features, such as VT earthquakes or thermal anomalies, were observed at the time, and the overall occurrence rate of earthquakes appears unchanged. This suggests that the source of the SP phase was destroyed rapidly, and that the LP phase was unaffected by the change. The most likely explanation is that the conduit obstruction that caused the SP phase was destroyed on November 21, although no associated seismic signal was observed. LP activity continued without trigger activity after the coupled events ended. The total number of events at Shishaldin remained similar following the cessation of the SP phase.

12. Discussion

The model proposed here indicates variations in SP–LP delay time are likely due to changes in gas content within the conduit. Events such as these can therefore provide insight into the amount of gas within the system and hence the state of unrest of the volcano. Because Shishaldin is not visible from any populated area, and because little is known about gas flux at the volcano, events such as the coupled earthquakes could provide a rare window into changes in gas content. At present, the conduit system at Shishaldin appears to be open, allowing constant degassing, so increases in gas flux may not indicate a hazardous change in the volcano’s plumbing system. In 1931, however, Hubbard (1935) reported that Shishaldin’s summit crater was filled with a solidified lava lake, indicating that it has the capacity of shutting
and blocking gas release. At a volcano with a closed system, events such as the coupled earthquakes could be used as an indicator of gas content for use in hazard evaluations.

As previously noted, there are times when SP–LP delay times vary significantly over short time scales (Figs. 4 and 5). More commonly, however, the LP phase seems to follow the SP phase within a few seconds of a predictable time (Figs. 4 and 5). This suggests that gas flux and gas content at Shishaldin usually exhibit relatively steady state behaviour, but occasionally fluctuate rapidly. There appear to be times (e.g. near June 1; Fig. 5), in which delay times suddenly increase markedly. This reflects the addition of new gas into the system. The sharp change from short delay times in April–June to consistently long delay times evident between June and October may indicate that a new fracture opened through which gas could enter the system. Increased gas content may be expected to correlate with increased gas flux at the vent, but no observations exist to evaluate this relationship. Periodic sealing of the crack could regulate delay times over short periods.

The presence of the SP phase is the key feature that defines a coupled earthquake. If this phase does indeed result from an obstruction in the conduit or other such feature, then it may be a simple case of good fortune that these signals occurred such that they could be identified and studied. However, earthquakes similar to Shishaldin coupled events have been noted on a handful of other volcanoes (Galeras, Gil Cruz and Chouet, 1997; Popocatepetl, R. White, personal communication, 2001; Stromboli, J. Lees, personal communication, 2002; Deception Island, Ibanez et al., 2003; Koryaksi, Gordeev and Senyukov, 2003), so they may be more common than has been previously noted. In other instances, the association between the two phases may not be noted, possibly due to the small amplitude of the SP phase. The increased popularity of cross-correlation techniques in the study of volcanic seismicity (e.g. Gillard et al., 1996; Lees, 1998; Aster and Rowe, 2000; Wolfe et al., 2003; Rowe et al., 2003; Battaglia et al., 2004) may promote the identification of similar types of events. We are therefore optimistic that this type of locally triggered seismicity may be found in other seismically active regions. Events such as these could provide a telling view on the internal structure of active volcanoes and a new means by which gas content can be remotely and safely monitored.

Acknowledgments

We are grateful to our colleagues at the Alaska Volcano Observatory, notably S.R. McNutt, for helpful discussions regarding Shishaldin seismicity. The work was greatly improved following helpful reviews by Timothy Horscroft, Eisuke Fujita and an anonymous reviewer. The manuscript further benefited from discussion with R. White and S. Prejean of the U.S.G.S. Several figures were produced using the Generic Mapping Tools software by Wessel and Smith (1998).

References


