Multiplets: Their behavior and utility at dacitic and andesitic volcanic centers

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Multiplets, or groups of earthquakes with similar waveforms, are commonly observed at volcanoes, particularly those exhibiting unrest. Using triggered seismic data from the 1980–1986 Mount St. Helens (MSH) eruption, we have constructed a catalog of multiplet occurrence. Our analysis reveals that the occurrence of multiplets is related, at least in part, to the viscosity of the magma. We also constructed catalogs of multiplet occurrence using continuous seismic data from the 2004 eruption at MSH and 2007 eruption at Bezymianny Volcano, Russia. Prior to explosions at MSH in 2004 and Bezymianny in 2007, the multiplet proportion of total seismicity (MPTS) declined, while the average amplitudes and standard deviations of the average amplitude increased. The life spans of multiplets (time between the first and last event) were also shorter prior to explosions than during passive lava extrusion. Dome-forming eruptions that include a partially solidified plug, like MSH (1983–1986 and 2004–2008), often possess multiplets with longer life spans and MPTS values exceeding 50%. Conceptually, the relatively unstable environment prior to explosions is characterized by large and variable stress gradients brought about by rapidly changing overpressures within the conduit. We infer that such complex stress fields affect the number of concurrent families, MPTS, average amplitude, and standard deviation of the amplitude of the multiplets. We also argue that multiplet detection may be an important new monitoring tool for determining the timing of explosions and in forecasting the type of eruption.


1. Introduction

Multiplets, earthquakes with similar waveforms, are observed in a variety of tectonic settings. At volcanoes, multiplets are commonly observed during dome building eruptive sequences (e.g., Mount St. Helens [Frémont and Malone, 1987], Soufriere Hills [Rowe et al., 2004], Augustine [Power and Lalla, 2010]) and during basaltic eruptions (e.g., Kilauea [Battaglia et al., 2003] and Etna [Saccorotti et al., 2007]) and also as volcano-tectonic earthquakes during noneruptive time periods. Likewise, multiplets are observed on transform fault systems such as the San Andreas Fault [e.g., Vidale et al., 1994; Nadeau et al., 1995; Rubin et al., 1999] and thrust fault systems such as in Taiwan [e.g., Chen et al., 2007]. The occurrence of multiplets in discrete fault systems is often associated with the repeated failure of fault asperities [Beeler et al., 2001; Chen et al., 2007; Dreger et al., 2007].

Studies including multiplets on volcanoes have largely leveraged the similarity between events to calculate highly precise locations and illuminate structures at depth [e.g., Got et al., 1994; Musumeci et al., 2002]. Fewer studies have studied the dynamic behavior of multiplets to assess conditions within a single volcano [Green and Neuberg, 2006; Grèt et al., 2005; Petersen, 2007; Umakoshi et al., 2008]. Unfortunately, each study uses a different methodology to identify multiplets and thus comparing the changes in multiplet occurrence or attributes between volcanoes with different properties can be difficult. The inability to compare multiplet characteristics and behavior across volcanic systems inhibits the use of multiplets as a volcano-monitoring tool because the general sensitivity of multiplets to changes in eruptive dynamics is yet to be established.

In this paper we first present a consistent methodology for identifying multiplets at Bezymianny Volcano (Russia) and Mount St. Helens (Washington; MSH). The resulting multiplet catalog is then analyzed for average earthquake amplitudes and standard deviations, multiplet life spans, number of concurrent multiplets and proportion of total seismicity consisting of multiplets (collectively referred to as multiplet characteristics). We focus on time periods...
around explosions and changes in eruptive style to assess how changes in eruptive behavior affect multiplet characteristics. We hypothesize that changes in stress or pressure within the vicinity of the multiplet source area, such as might be expected prior to an eruption or during a change in eruptive style, are reflected by changes in the occurrence of multiplets and multiplet characteristics. We generalize these patterns and changes in parameters by comparing multiplets at Bezymianny and Mount St. Helens and reviewing the published record of multiplet occurrence at volcanoes with similar compositions. Our analysis is confined to volcanoes with dacitic and andesitic compositions in order to reduce the number of free parameters when interpreting our results. Through our analysis, we show that multiplet characteristics change prior to large explosions and are distinctly different between unstable (e.g., explosions) and stable (e.g., passive dome building) regimes. We also show that multiplets are most common during certain dome-building phases where a hot, viscous and actively degassing plug is present.

Our study initially focuses on two volcanoes with similar eruptive histories, quality of seismic records, and availability of prior documentation of multiplet occurrence. Bezymianny Volcano (Kamchatka, Russia) had a cryptodome emplacement and subsequent edifice failure in 1956 that was remarkably similar to the 1980 eruption at Mount St. Helens [Bogoyavlenskaya et al., 1985; Thelen, 2009]. Since 1956 the volcano has had several different phases of activity, most recently including large explosions and effusive lava flows [Belousov et al., 2002]. Bezymianny often has more than one eruption in a given year, and multiplets are known to accompany at least some of these eruptions [West et al., 2007]. A network of broadband instruments was installed around Bezymianny Volcano beginning in 2006, providing excellent on-scale recordings of several eruptive phenomena (Figure 1) [Thelen, 2006]. The network eventually grew to include 8 stations, all sampled at 100 Hz, which all recorded on site. In this study, we only used the vertical channels from BESA, BERG and BELO.

The 1980–1986 eruption at MSH provides a well-studied eruptive sequence and an excellent opportunity to search for the occurrence of multiplets during many different types of activity, from cryptodome emplacement to explosive activity to discrete dome-forming activity. Frémont and Malone [1987] published the first documented instance of multiplet occurrence during eruptions in 1983 and 1984, and on their increased occurrence as the discrete dome-building phase continued. The seismicity associated with the 2004–2008 continuous dome-building eruption was dominated by multiplets [Moran et al., 2008b; Thelen et al., 2008]. The permanent seismic network at MSH has been relatively dense since the onset of activity in March 1980. The network is dominated by Mark Products L4 short-period seismometers with a natural period of 1 Hz and a sampling frequency of 100 Hz. Broadband instrumentation was installed in response to the eruption in 2004, but was not used in this study because the data was incomplete through the study period. Since March 1980, the permanent real-time network at MSH has had a minimum of 5 stations...
within 15 km (excluding posteruptive outages) and a maximum of 20 stations within 15 km.

2. Methods

[7] To better understand the occurrence of multiplets, we constructed a catalog of multiplet occurrence from the continuous seismic record at both MSH and Bezymianny. The process is as follows: a seismic event was declared if a short-term average to long-term average (STA/LTA) ratio of the Hilbert transformed seismic trace exceeded a threshold (2.5) on 2 out of 3 analyzed stations within 5 s (Table 1). Utilizing multiple stations for the detection of seismic events provided more robust triggering and subsequent multiplet analysis because false triggers from sources of noise local to a particular station (e.g., radio interference, nearby wildlife, aircraft) were minimized.

[8] The sheer number of events to compare (>55,000 detected events at MSH, >8,000 detected events at Bezymianny) precludes the direct comparison of individual events throughout the study period and requires a methodology to compare and combine multiplets in discrete batches. Our strategy is to detect multiplets occurring within a given day, then combine common multiplets between days by comparing daily stacks of multiplet waveforms.

Table 1. List of Parameters Used for Multiplet Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bezymianny</th>
<th>Mount St. Helens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stations</td>
<td>BELO, BESA, BERG</td>
<td>SHW, HSR, SOS</td>
</tr>
<tr>
<td>Filter band for event detection</td>
<td>2–10 Hz</td>
<td>None</td>
</tr>
<tr>
<td>correlation and STA/LTA threshold</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of stations required for</td>
<td>2 out of 3</td>
<td>2 out of 3</td>
</tr>
<tr>
<td>detecting seismic event</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window length (samples in parentheses)</td>
<td>9 s (900 samples),</td>
<td>9 s (900 samples),</td>
</tr>
<tr>
<td></td>
<td>2 s before,</td>
<td>2 s before,</td>
</tr>
<tr>
<td></td>
<td>7 s after trigger</td>
<td>7 s after trigger</td>
</tr>
<tr>
<td>Daily CCC threshold</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Combine CCC threshold</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

[10] The initial comparison and collation of similar waveforms occurs on a day-by-day basis using all events that occurred within a given day. Within each day, we considered a 9 s window (2 s before, 7 s after; 900 total samples; Table 1) around each trigger and constructed an N event × N event matrix of maximum cross-correlation coefficients (CCC) (e.g., Figure 2a). Practically, each row of the cross correlation matrix represents a single triggered event compared to every other triggered event on that day. To begin extracting multiplets from the daily cross-correlation matrices, we calculated the mean CCC for each row in the matrix, a method similar to Petersen [2007]. The difference between our method and that used by Petersen [2007] was the requirement of a CCC above the CCC threshold on two out of three stations. No event is permitted to belong to more than one multiplet. In our analysis, we selected a CCC threshold of 0.7 because it is the lowest threshold for which we could visually confirm similarity between events. We feel the ability to visually confirm the quality of our results is critical and thus resist using lower CCC thresholds as other studies have [e.g., Battaglia et al., 2003; Umakoshi et al., 2008]. The CCC of random signals results in a normal distribution [Green and Neuberg, 2006]. Choosing a CCC above the expected normal distribution will thus properly classify similar (nonrandom) events. Our threshold selection of CCC = 0.7 is above the normally distributed distribution of CCC values and thus appropriate to separate nonrandom signals (Figure 2b). Our combination of time window (9 s), effective signal bandwidth (5 Hz for most low-frequency events), CCC (0.7) and number of stations (2 out of 3) results in a probability of ≤1% of two events being falsely attributed to the same multiplet [Harris, 1991].

[11] Multiplets may have a life span of days to weeks that cross many day boundaries and thus we must devise a method to combine multiplets that are detected on different days. To combine multiplets that occurred on more than 1 day, we stacked all members of each multiplet on each day for each station and compared all of the stacks on each station using the same method described in the daily anal-

Figure 2. (a) Cross-correlation matrix of earthquakes on 25 September 2004 from Mount St. Helens. (b) Histogram of cross-correlation values showing a normal distribution at low cross-correlation values.
ysis. To reduce the computing load in the combination step, we only considered multiplets with a population of two or more events. Our intention was to identify multiplets with life spans of several days with events possessing CCC at or above the initial (daily) CCC threshold (0.7). To achieve this goal with the method above, we combined the stacks of the daily multiplets with a slightly higher CCC threshold (0.8, Table 1). Because the member events of each multiplet are rarely perfectly correlated to the stack, a higher CCC threshold in the combination step helped ensure that most member events within the multiplet met the initial (daily) CCC threshold. Alternatively, a lower CCC threshold in the combination step combined more multiplets across day boundaries, though the member events of the multiplets were more poorly correlated. Our selection of a CCC = 0.8 in the combination step reflects a tradeoff between maintaining reasonable CCC of the member events within the finalized multiplets and reducing artifacts from the combination of multiplets across day boundaries.

[12] In this paper, we analyze several characteristics of the multiplet catalog including life span (the time difference between the first and last event in a multiplet) and the multiplet proportion of total seismicity (MPTS, the percentage of events in a multiplet with respect to the total number of triggered seismicity), and number of concurrent multiplets (number of active multiplet sources active at a given time). Due to the evolving nature of multiplet waveforms, life spans may be particularly biased by our choice of CCC. A lower CCC threshold will allow for more evolution in the waveform, and thus a longer life span before reaching the CCC threshold. Likewise a higher CCC threshold will result in shorter life spans as an evolving waveform will decorrelate faster with other events of the multiplet. Because an event uniquely tied to a multiplet, the MPTS and number of concurrent multiplets is mostly unaffected by evolving waveforms. In general, if multiplets do not change, a lower CCC will combine more multiplets that would have been otherwise split, and thus the life spans would be longer. By keeping the CCC constant between Mount St. Helens and Bezymianny, we can effectively compare multiplet catalogs and the absolute values of parameters that are derived from those catalogs.

[13] Our characterization of MPTS is prone to some limitations. The MPTS is affected by the choice of CCC as a high CCC will result in fewer correlations between events, more events that do not belong to a multiplet, and a lower MPTS. The MPTS may also be biased by regional seismicity, local seismicity not occurring near the conduit or seismicity associated with surface processes, such as glaciers or rockfall. In general, we find that regional seismicity or seismicity from neighboring volcanoes is insignificant in numbers with respect to the overall seismicity. Particularly at Bezymianny, we have chosen a time period where seismicity at nearby Kluchevsky volcano is low. Volcano tectonic (VT) swarms may occur away from the conduit and could be included in the estimate of total seismicity. During the chosen time periods at both volcanoes, no VT swarms occurred that would have significantly skewed the estimate of MPTS. Rockfall, which is particularly common during times of unrest at Bezymianny, may have a real affect on the MPTS. During times of increased rockfall, the MPTS may decrease as rockfall signals are unlikely to be grouped into a multiplet. This is addressed in the discussion of multiplets at Bezymianny volcano. Glacial seismicity was not significant with respect to the total seismicity at Mount St. Helens or Bezymianny.

[14] In order to detect multiplets in the 1980–1986 eruption of Mount St. Helens, we must adjust the method slightly because a continuous seismic record for the eruption is not available. Continuous data have only recently been available due to advances in disk size and reduction in cost. Networks instead stored event waveforms from automatic triggers, which underreports the activity by up to 97% in some extreme cases [Qamar et al., 2008; Rowe et al., 2004]. The 1980–1986 seismic record at MSH is made up of a subset of events automatically triggered and located by the Pacific Northwest Seismic Network (PNSN). While the data set is clearly not a comprehensive record of seismicity between 1980 and 1986, it is representative of the strongest seismicity occurring at the time, and should suffice to compare the relative abundance of multiplets in a variety of volcanic stages. Because of the incomplete nature of the triggered data set, we resist calculating many multiplet characteristics as we did at Bezymianny and the 2004 eruption of MSH, which are dependent on having a nearly complete seismic record.

[15] In our study of the 1980–1986 seismicity, we considered all triggered events. This included located events, along with events that did not have enough phase picks to be located. We used 8 s windows in the analysis, including 1 s prior to the pick time. Because we are using more precise analyst phase picks, we do not need to use as large of a window prior to the phase pick as we did using the automatic picks within the continuous data. While some stations are consistent across years, the seismic network at MSH was rapidly changing, and in most cases, the station configuration between years was different. As such, we were required to use different stations between years for multiplet detection. Stations were selected based on their proximity to the volcano and consistent data quality.

[16] The method of identifying multiplets in the 1980–1986 seismic record was the same as that used in the continuous data although the seismic events had already been selected as part of the triggered data set. As above, the CCC threshold was set to 0.7 and the event had to be similar at the CCC threshold on two out of three stations. Because of the relatively low number of triggered seismic events saved, instead of considering a day at a time (like the 2004 multiplet catalog), each year was considered as a whole. As such, multiplets with member events that have less than two member events per day are included in the analysis.

3. Multiplet Catalog Observations

3.1. Bezymianny Volcano

[17] The multiplet catalog from Bezymianny is the same as that presented by Thelen et al. [2010] (Figure 3). The time period of this study was 1 September 2007 to 1 December 2007, encompassing three different volcanic phenomena. The events on 25 September and 5 November were a small explosion and a dome collapse, respectively. Both were surficial events that did not affect the deeper magmatic system [Thelen et al., 2010]. A larger eruption occurred on 14 October consisting of several explosions,
pyroclastic flows, lava flows and significant seismic activity within the deeper magmatic system [Thelen et al., 2010]. Increases in RSAM (Figure 3) around the 14 October were due largely to increased rockfall from the oversteepened dome. Table 2 summarizes the eruptive activity and the contemporary changes in multiplet behavior from Thelen et al. [2010]. Seismicity throughout the study period was dominated by low-frequency earthquakes (dominant energy <5 Hz) and with some short periods of tremor near the 14 October explosion. Multiplets at Bezymianny were overwhelmingly composed of low-frequency earthquakes with only a couple exceptions [Thelen et al., 2010]. All earthquakes had magnitudes less than 2. Multiplet waveforms generally evolved slowly with time. Most multiplets were not recorded on stations outside the edifice of the volcano and were likely located at shallow depths below the dome. Multiplets that were large enough to be formally located occurred under the volcano and to the north with depths of 0.5–6 km, coincident with the locations of non-multiplet events.

[18] We used the multiplet catalog from Bezymianny to further quantify average amplitude, standard deviation, life span and proportion of total seismicity of the multiplets to determine how they changed during the volcanic activity at Bezymianny. The average maximum amplitude of each multiplet and the standard deviation of the average maximum amplitude (a measure of variability in maximum amplitudes within a single multiplet) were unchanged through the September and November unrest (Figure 4). However, prior to and after the October eruption the average maximum multiplet amplitudes increased to values higher than at any other time during the study period. The increase in amplitudes began shortly after the September unrest (Figure 4). The average maximum amplitudes then decayed to relatively low values throughout the end of October and November. The standard deviation of the maximum amplitudes of the seismic events within each multiplet showed similar patterns to the average maximum amplitudes. At times, high standard deviations were associated with periods of high RSAM (Figure 4). The correlation of high average

**Table 2.** Summary of Eruptive Activity and Multiplet Behavior at Bezymianny From September to November 2007

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Event description</td>
<td>minor precursory seismicity, small eruptive plume, and no juvenile material</td>
<td>7 days strong precursory seismicity, large explosion plus pyroclastic flows, and deep post-eruptive seismicity</td>
<td>no precursory seismicity, no juvenile material, and dome collapse</td>
</tr>
<tr>
<td>Number of concurrent multiplets</td>
<td>NC</td>
<td>decreased</td>
<td>NC</td>
</tr>
<tr>
<td>Multiplet duration</td>
<td>NC</td>
<td>decreased</td>
<td>NC</td>
</tr>
<tr>
<td>Multiplets destroyed?</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

*aKamchatka Branch of Geophysical Survey [2007a, 2007b, 2007c] and Thelen et al. [2010]. NC refers to no change.*

**Figure 3.** Catalog of multiplet occurrence at Bezymianny Volcano, Russia. Each circle represents an earthquake, and earthquakes on the same line are part of the same multiplet. The light gray line is the RSAM measured on station BELO. Black vertical lines represent large explosions, and dashed black vertical lines are small explosions or dome collapses. Modified from Thelen et al. [2010], copyright 2010, with permission from Elsevier.
amplitudes and high standard deviations with high levels of RSAM may suggest that the high activity levels have obscured the detection of small events, leading to a biased multiplet population. Despite the high RSAM, the detection of multiplets was unhindered during periods of high RSAM around the October eruption [Thelen et al., 2010]. Thus the multiplets occurring around the 14 October eruption were of higher average amplitude with more variability than other times during the study period.

Other quantifiable multiplet parameters show variable change based on the size and type of eruption or phenomenon. The life span, or duration, is defined as the length of time between the first and the last event of the multiplet. During much of the study period, multiplets had life spans of about 2 weeks (Figure 4). Prior to the 14 October eruption, which was significantly larger than either the September or November activity, the life span of the multiplets clearly declined. After the 14 October eruption, life spans returned slowly to 2 week life spans, similar to background periods in September and November.

The number of concurrent multiplets also changed during the 14 October 2007 eruption (Figure 5). The number of concurrent multiplets is defined as the number of multiplets with its first event prior to a given time and its last event after a given time. The parameter quantifies the number of distinct multiplet sources present at any one time. The number of concurrent multiplets increased despite the September unrest, and then dropped prior to the October eruption. After the October eruption, the number of concurrent multiplets again increased despite the November dome collapse.

The multiplet proportion of total seismicity (MPTS) is generally between 10% and 20% for the entire time period (Figure 5). The total seismicity refers to all of the automatically detected seismic events in the initial stage of constructing a multiplet catalog. Trends in the MPTS followed trends in the number of concurrent multiplets. In the days prior to the October eruption, the MPTS dropped significantly. The 14 October eruption at Bezymianny was accompanied by increases in the occurrence of rockfall, which would decrease the MPTS, even if the multiplet rate of occurrence was the same. The rate of multiplet occurrence declined during this time period as well, even when using different and more sensitive techniques to detect multiplets [Thelen et al., 2010]. Thus the MPTS decline prior to the 14 October eruption at Bezymianny is real, though it may not have been as dramatic as shown in Figure 5. The MPTS also decreased prior to the September unrest, although the significance of the drop is questionable given the variability in MPTS during that time period.

Figure 4. (a) Average amplitude and (b) standard deviation about the average for each multiplet at Bezymianny in Figure 3. Black line is RSAM values on station BELO. (c) Life span of multiplets, defined as the difference in time between the first and last events in a given multiplet. Each solid circle represents one multiplet. Vertical black lines represent large explosions, and dashed vertical lines represent small explosions or dome collapses.
The number of concurrent multiplets (light gray) and the multiplet proportion of total seismicity (MPTS, dark gray) for multiplets at Bezymianny. Both parameters were calculated every 12 h. Dark vertical lines represent large explosions, while dashed vertical lines represent small explosions or dome collapses.


[22] The 1980 to 1986 eruption of Mount St. Helens consisted of several different types of volcanic phenomena. The most famous eruption in U.S. history occurred on 18 May 1980. Subsequent activity during 1980 included smaller (though still significant) explosions on 25 May, 12 June, 22 July, and 16–18 October [Christiansen and Peterson, 1982]. Dome building began during the June explosion, however a persistent dome (one not destroyed by an eruption) did not form until after the 16–18 October explosion [Christiansen and Peterson, 1982]. The dominant type of activity from 1981 to 1986 was in the form of discrete dome building, where dome growth occurred during punctuated sequences of seismicity and deformation with quiescence between extrusive phases [Neri and Malone, 1989; Swanson et al., 1985]. One phase of continuous extrusive dome building began on 7 February 1983 and lasted for over a year [Swanson and Holcomb, 1990]. Discrete dome building episodes continued after the continuous phase and generally released more seismic energy than prior discrete eruptive phases [Neri and Malone, 1989].

[23] Multiplets were present throughout many of the eruptions between 1980 to 1986 (Figure 6). Prior to the catastrophic eruption in 1980 there was weak development of multiplets in earthquakes included within the seismic catalog. Earthquakes within multiplets generally had peak frequencies below 5 Hz and were located at depths of less than 2 km under the edifice. Unfortunately, a very small proportion of the overall seismicity during the precursory phase of the 1980 eruption (16 March 1980 to 18 May 1980) is represented in the catalog due to limitations in computing resources in storing waveform data and the challenge of manually timing phase picks and locating earthquakes. During the highest rates of seismicity, the number of located earthquakes was as much as 6 times less than the number of manually counted earthquakes. After the cataclysmic eruption on 18 May 1980, seismic activity was not as intense and thus the catalog contains a higher percentage of the total seismicity that occurred. Most of the multiplets in 1980 occurred after the 18 May eruption in the form of deep (4–12 km) high-frequency earthquakes (Figure 6). Few multiplets occurred through the smaller explosive eruptions during the precursory and extrusive phases of the eruptions between 1984 and 1986. Earthquakes within the multiplets before and after each eruption had no obvious difference in recurrence interval or peak frequency. Multiplet development was generally confined to periods around eruptions when earthquake rates were high. Multiplets containing events with low recurrence intervals (<1 day) generally only last one eruption cycle.

3.3. Mount St. Helens: 23 September 2004 to 31 October 2004

[25] The continuous seismic record present during the 2004–2008 eruption of Mount St. Helens allows for a complete characterization of multiplet occurrence. We present the multiplet catalog from the initial phreatic phase (23 September 2004 to October 2004) through approximately 1 month of the dome extrusion (31 October 2004). A synopsis of the activity during the study period is given by Moran et al. [2008b]. We did not formally locate any detected multiplets at Mount St. Helens as part of this study, however, all located earthquakes during the study period had depths between 0 and 1.5 km below the 1980–1986 dome [Thelen et al., 2008]. Some formally located earthquakes included earthquakes within our detected multiplets, and thus we expect that the presented multiplets also have depths between 0 and 1.5 km depth.
The first multiplets appeared soon after the onset of high-frequency (VT) seismicity on 23 September 2004 (Figure 7). Between 23 September 2004 and 26 September 2004 multiplets had high MPTS, sometimes over 80% (Figure 8), and up to 22 concurrent multiplets were present (Figure 8). Multiplets during this time period had magnitudes up to M 2. The life span of multiplets measured on the near-field stations did not significantly change from 23 September to 25 September (Figure 9). Earthquakes within multiplets between 23 September and 26 September were high frequency (peak frequencies >10 Hz) in character (VT), similar to nonmultiplet seismicity occurring during that time (Figure 10).

As the initial swarm of VT seismicity waned, most of the multiplets in the initial swarm ended (Figure 7). Low-frequency and hybrid seismicity abruptly increased on 26 September 2004, mirroring an increase in MPTS, the number of concurrent multiplets, and average amplitude of multiplets (Figures 8, 10, and 11). Earthquakes within multiplets also had hybrid and low-frequency characteristics during this time period (Figure 10). Immediately after a peak in MPTS on 26 September 2004, the MPTS decreased and remained at a lower level through the first explosion on 1 October (Figure 8), even though hybrid and low-frequency seismicity rapidly increased on 29 September. Between 29 September and 5 October, numerous high-amplitude earthquakes often resulted in clipping and overlapping codas on near-field stations. Earthquake magnitudes were up to M4. To test the effect of clipping and overlapping codas on our results, we constructed a multiplet catalog using stations further from the edifice, which did not clip. Between 29 September and 5 October the multiplet catalog using stations further from the edifice showed similar trends in concurrent multiplets and MPTS to the near-field catalog, supporting the integrity of the trends in the near-field catalog during time periods when signal clipping was common.

Figure 6. Multiplet catalog at Mount St. Helens between 1980 and 1986 using the triggered seismic record. Gray lines represent the number of triggered events per day. Dark vertical lines represent eruptions as defined by Swanson and Holcomb [1990].
During the explosive precursory phase from 1 October to 5 October multiplet occurrence was variably correlated with surface explosions and shallow tremor. The explosions between 1 October and 5 October were minor with no explosion exceeding a plume height over 3 km above the crater [Moran et al., 2008b]. While a short hiatus in seismicity occurred after the 1 October explosion and subsequent harmonic tremor, several multiplets that were

**Figure 7.** Catalog of multiplet occurrence at Mount St. Helens during the beginning of the 2004 eruption. Only multiplets with five or more events are shown. Multiplets and RSAM are represented as in Figure 3. RSAM is calculated using station SHW. (a) Multiplet catalog between 23 September 2004 and 11 October 2004. Vertical dashed lines are explosion times [Moran et al., 2008a], and gray circles between 2 and 4 October 2004 are times of tremor. (bottom) Multiplet occurrence during dome building between 11 and 31 October 2004.

[28] During the explosive precursory phase from 1 October to 5 October multiplet occurrence was variably correlated with surface explosions and shallow tremor. The explosions between 1 October and 5 October were minor with no explosion exceeding a plume height over 3 km above the crater [Moran et al., 2008b]. While a short hiatus in seismicity occurred after the 1 October explosion and subsequent harmonic tremor, several multiplets that were

**Figure 8.** The number of concurrent multiplets (black) and the multiplet proportion of total seismicity (MPTS, gray) at MSH. Each multiplet is plotted with respect to the mean time of the earthquakes within the multiplet. Both parameters were calculated every 12 h. Dashed vertical lines represent small explosions.
Figure 9. (a) Multiplet life spans from the multiplet catalog at MSH. Each multiplet is plotted with respect to the mean time of the earthquakes within the multiplet. Vertical dashed lines are explosion times. (b) Histogram of multiplet life spans before and after the initial explosive phase of the eruption.

Figure 10. (a) Generalized earthquake occurrence for all earthquakes during the study period at MSH from Moran et al. [2008b]. Dashed lines represent times of transition between earthquake types. (b) Averaged peak frequency for earthquakes within multiplets at MSH.
present before the explosion continued when seismicity began again (Figure 7). A strong period of noneruptive tremor on 2 October (28–43 cm$^2$ reduced displacement [Moran et al., 2008b]) coincides with the termination of some multiplets; however, a weaker noneruptive tremor episode on 3 October (10–20 cm$^2$ reduced displacement [Moran et al., 2008b]) did not correlate with a change in the behavior of multiplets occurring at that time. Small explosions on 4 October and 5 October were not associated with a change in the occurrence of multiplets (Figures 7–11). The standard deviation of the average amplitude of the multiplets had their highest values between 1 October and 5 October, coincident with the highest values of RSAM during the study period (Figures 10c and 10d). Increased RSAM levels were due to increases in earthquake rates and earthquake amplitudes, with tremor only occurring during a couple of discrete time periods. After the 5 October explosion, RSAM (and event amplitudes) declined dramatically, and never regained values seen between 30 September and 5 October. Shortly thereafter, and correlated with a modest increase in RSAM, a new set of multiplets began (Figure 7). No multiplet occurring prior to the increase in RSAM on 8 October occurred again during the study period.

[29] The first appearance of juvenile material occurred on 11 October 2004 [Vallance et al., 2008]. The appearance of juvenile material was accompanied almost exclusively by low-frequency seismicity [Moran et al., 2008b]. Earthquakes within multiplets after 11 October 2004 were also low frequency in character and had magnitudes up to M2.5 (Figure 11). The emergence of lava at the surface was concurrent with the appearance of long-life span multiplets with lower average amplitudes than those recorded between 1 October and 5 October (Figure 9). The standard deviations of the average amplitudes of the multiplets often followed trends in the RSAM values during the study period (Figure 11). Multiplets waveforms generally evolved slowly with time.

4. Discussion

4.1. Physical Controls on the Development of Multiplets

[30] In order to compare multiplet abundance at different volcanoes with different quality data sets, we define a new characteristic, multiplet efficiency. For the purposes of this discussion, we qualitatively define high multiplet efficiency as the ability of a system to generate many multiplets that each has many member earthquakes with short (~hours) recurrence intervals. In eruptions with data that permit the calculation of MPTS (e.g., MSH 2004 and Bezymianny 2007), MPTS values above 50% may be considered as time periods having high multiplet efficiency. Generally explosions at Mount St. Helens, with or without subsequent dome building, between 18 May 1980 and 1982 had a low mul-
Table 3. Comparison of Multiplet Characteristics at Mount St. Helens and Bezymianny Volcano

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td>Stable (6–31 Oct)</td>
<td>Unstable (23 Sep to 6 Oct)</td>
</tr>
<tr>
<td>Average amplitude</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Standard deviation of average</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Duration</td>
<td>hours to 2 weeks</td>
<td>hours–days</td>
</tr>
<tr>
<td>Concurrent multiplets</td>
<td>5–60, mostly &gt;20</td>
<td>10–22</td>
</tr>
<tr>
<td>Multiplet percentage</td>
<td>30%–90%</td>
<td>35%–85%, decreasing</td>
</tr>
</tbody>
</table>

| of total seismicity     | prior to eruption       | prior to eruption | prior to eruption |

Terms such as “high” and “low” are in reference to other multiplets during the study period at a particular volcanic center.

Multiplet efficiency. Later in the Mount St. Helens eruption, particularly between 1983 and 1986, dome-forming eruptions were accompanied by higher multiplet efficiencies. [31] As multiplet occurrence generally increased throughout the eruption, extrusion rates dropped [Swanson and Holcomb, 1990], Assuming a constant diameter of the conduit during the 1980–1986 eruption at Mount St. Helens, extrusion rate can be used as a proxy for ascent rate. As extrusion rates decreased, magma spent more time in the conduit, increasing gas loss and resulting in crystallization and increasing magma viscosity [Sparks, 1997]. A change from gas-rich scoriacious dome textures to gas-poor smooth dome textures between 1980 and 1986 is evidence for progressively more degassing within the conduit with time [Anderson and Fink, 1990]. Further contributing to an increase in viscosity, the silica content of the extruded domes increased between 1980 and 1986 [Pallister et al., 1992]. The 2004 eruption at MSH also had high multiplet efficiency that coincided with the extrusion of solidified and highly degassed spines that formed up to 1 km below the vent [Pallister et al., 2008]. Thus it is clear that multiplets efficiency was higher when viscosities of magmas within the conduit were relatively high. Because of this dependence on viscosity, multiplet occurrence alone may not be a good measure of extrusion rate. [32] High multiplet efficiency may also be achieved in the presence of a relatively gas-charged magma in a sealed system, as occurred in the explosive eruption in March 1982 at MSH. Clearly the multiplet efficiency was higher before the eruption than after the eruption (Figure 6). After the eruption, the rate of SO2 doubled from preeruptive levels, implying a change from a closed to an open system after the explosion [McGee and Casadivan, 1994]. The occurrence of deep seismicity prior to the 1982 eruption is interpreted as increased gas flux from depth [Weaver et al., 1983]. The presence of only precursory multiplets with dominantly low-frequency characteristics suggests that, their occurrence was related to enhanced degassing within the conduit from additional gases accompanying the eruption trapped within a closed system. We infer that the low multiplet efficiency after the explosion and subsequent dome building was related to increased extrusion rates after the explosion that limited degassing within the conduit, thus keeping the viscosity of the magma low. [33] In contrast, extrusion during the October 2007 Bezymianny eruption consisted principally of lava flows down the side of the dome [Thelen et al., 2010], and low multiplet efficiencies (MPTS < 20%). Previous eruptions at Bezymianny, similar to the October 2007 eruption, were observed to push out a cold and dense plug prior to explosive eruptions and lava flows [Belousov et al., 2002]. No multiplets have been reported from these eruptions implying low multiplet efficiencies and relatively low viscosity magma, as was observed during the 2007 eruption. [34] In summary, during the entirety of the 1980–1986 MSH eruption, except the March 1982 eruption, and during the 2004–2008 MSH eruption high multiplet efficiencies were primarily associated with the ample degassing within the shallow conduit, leading to a relatively viscous magma. At Bezymianny, low multiplet efficiencies are associated with relatively low viscosity magmas that result in flows instead of domes. The relationship between multiplet efficiency and viscosity can be utilized to make inferences about the physical conditions of magma in the conduit, potentially leading to more informed short-term forecasts of the likely nature of future eruptions.

4.2. Comparison of Behavior at Bezymianny and 2004–2008 Mount St. Helens

[35] When quantified, the characteristics of multiplets at both volcanoes can be divided into those associated with unstable and stable time periods. Stable time periods may contain dome extrusion, lava flows or brief periods of quiescence, without the presence of large explosions. Stability is used in a relative sense at a particular volcano. At both volcanoes the average amplitudes and amplitude variability (standard deviation) of each multiplet was higher during unstable time periods leading up to explosions than during stable time periods where extrusion was present (Figures 4a, 4b, and 11 and Table 3). Generally, the life spans of multiplets during the 2004 MSH eruption and 2007 Bezymianny eruption were shorter during unstable time periods leading up to explosions than during stable time periods containing extrusion (Figures 4c and 9b and Table 3). The MPTS at both volcanoes did not have significantly different values during stable and unstable time periods, however the MPTS dropped significantly prior to the 2 October explosion at MSH, and prior to the 14 October eruption at Bezymianny (Figures 5 and 8). The number of concurrent multiplets was generally lower in unstable time periods than in stable time periods at MSH and Bezymianny, though the trends in concurrent multiplets leading up to explosions were different (Figures 5 and 8).

[36] Based on observed differences in multiplet characteristics during different volcanic phenomena at Bezymianny and MSH, we may link pressure changes to multiplet behav-
Table 4. Common Characteristics of Multiplets During Unstable and Stable Time Periods*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Unstable</th>
<th>Stable</th>
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<tbody>
<tr>
<td>Multiplet percentage of total seismicity (MPTS)</td>
<td>low&lt;sup&gt;b,c,d&lt;/sup&gt;, high&lt;sup&gt;e,f&lt;/sup&gt; declined prior to explosion&lt;sup&gt;b,c,z&lt;/sup&gt;</td>
<td>high&lt;sup&gt;e,h&lt;/sup&gt;</td>
</tr>
<tr>
<td>Duration</td>
<td>hours&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>days&lt;sup&gt;f,i&lt;/sup&gt; to weeks&lt;sup&gt;i&lt;/sup&gt;</td>
</tr>
<tr>
<td>Concurrent multiplets</td>
<td>low&lt;sup&gt;b,c,d&lt;/sup&gt;</td>
<td>high&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Variability</td>
<td>high&lt;sup&gt;c,h&lt;/sup&gt;</td>
<td>low&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

*Explosive eruptions are defined by plinian and subplinian eruption columns. A high MPTS is defined as >20%. High concurrent multiplets are defined as >5. Variability refers to the event amplitudes within multiplets. A low variability refers to stable amplitudes of events within a multiplet. The amplitudes may still change slowly with time. A high variability means that the amplitude of events within multiplets is variable.

1. Bezymianny, 2006 [West et al., 2007].
2. Bezymianny, 2007 (this paper).
5. Mount St. Helens, 2004 (this paper).

ior. At Bezymianny, a small surficial explosion on 25 September 2007 and a minor dome collapse on 5 November 2007 were not obviously correlated with a change in any multiplet characteristic in this paper. Both phenomena were quite small and likely had little effect on the underlying pressures within the conduit. Conversely, the large explosion on 14 October 2007 did correlate with changes in several multiplet characteristics, as well as the termination of all multiplet sources that were active prior to the eruption. Posteruption seismicity was up to 8 km deep, suggesting stress and/or pressure changes occurred at those depths [Thelen et al., 2010]. At MSH, the 1 October explosion was associated with a ~3 h cessation of earthquakes, including multiplets [Moran et al., 2008a, 2008b]. No other explosion was accompanied by such a cessation and we infer that this eruption possessed the largest pressure drop of any explosion between 1 October 2004 and 5 October 2004. Similarly, between the two tremor episodes, only the strongest of the two (measured by reduced displacement) on 2 October 2004 were correlated with a change in the occurrence of multiplets. Taken together it appears that the most significant changes in multiplets occurred during time periods when the largest pressures and/or stresses were present within the conduit.

4.3. Comparison of Multiplets at Other Volcanoes

[37] The lack of a published record of multiplets on a particular volcano does not mean that they did not occur, only that they were not likely a distinguishing feature of the overall seismicity. Multiplets are usually only recognized in cases when the largest events during a particular period are part of an earthquake family or when the dominant seismicity is made up of a limited number of different multiplets. When many families are active simultaneously, it is often difficult to visually detect and track individual families with time unless the families have a distinguishing characteristic. Particularly in cases when the MPTS is low, it is hard to track multiplets manually. With these difficulties in mind, we summarize the occurrence of multiplet reported in the literature at other volcanoes to assess the generality of patterns described above for MSH and Bezymianny.

[38] Seismicity at Unzen Volcano (Japan) during its dacitic dome-forming eruption from 1990 to 1995 was dominantly composed of multiplets made of both VT and low-frequency earthquakes [Umakoshi et al., 2008]. Dome growth was both endogeneous and exogenous, with solidification of magma occurring within the conduit at 600 m to 1.2 km depth, similar to conditions at MSH [Nakada et al., 1995]. Events within each family changed slowly with time (low standard deviations) and the duration of most families was up to 2 weeks [Umakoshi et al., 2008], similar to stable time periods at MSH and Bezymianny.

[39] At Soufriere Hills Volcano (Montserrat) the presence of multiplets is well documented during the early part of the 1995–present eruption [Green and Neuberg, 2006; Rowe et al., 2004; White et al., 1998]. Multiplet life spans ranged from days, during phreatic explosions, to weeks after dome extrusion began [White et al., 1998]. The shift in multiplet life span between unstable and stable periods at Soufriere Hills Volcano is consistent with our observations of life spans at MSH and Bezymianny. Dome growth at the Soufriere Hills Volcano was dominated by spines between November 1995 and September 1996, suggesting ample degassing from a viscous plug within the conduit [Watts et al., 2002], similar to the 2004 eruption at MSH. Green and Neuberg [2006] conducted a detailed analysis of multiplets during a period of dome growth and collapse in June 1997. Four or more concurrent multiplets were associated with much of this phase, although the occurrence of the multiplets was strongly modulated by changes in near-field deformation. The single dome collapse (25 June 1997) within the study period caused a shift in the dominant multiplet and up to 28 h of quiescence in some multiplets. The dominant multiplet before the 25 June collapse had higher average amplitudes and than those multiplets that were dominant after the collapse [Green and Neuberg, 2006], similar to shifts in amplitude between unstable and stable periods at MSH and Bezymianny. After the June 1997 explosion and collapse, dome building was dominantly through the extrusion of blocky lobes with minor spine development [Watts et al., 2002], suggesting that the material within the conduit during the collapse was relatively viscous.

[40] Multiplets were also documented prior to and during explosive phases of eruptions, such as Redoubt Volcano (Alaska) in 1989. Beginning approximately 19 h before the first explosion, three distinct multiplets dominated the seismic record [Stephens and Chouet, 2001]. Events within the dominant preruptive multiplets had amplitudes that varied over several orders of magnitude, implying a relatively high standard deviation similar to unstable time periods at MSH and Bezymianny. The multiplets lasted only a few hours prior to the first eruption, similar to life spans at MSH and Bezymianny during unstable time periods. Multiplets ceased, and thus the MPTS decreased, prior to the first explosion, similar to the unstable period prior to the 14 October eruption at Bezymianny.
Figure 12. Conceptual model of multiplet development. In this model, magma and gas move up the conduit. Overpressure within the conduit and escaping gases out of the conduit impart stresses on the edges of the conduit and on cracks surrounding the conduit. Multiplets may occur either in cracks around the conduit or along the shear zone at the edge of the conduit.

[41] The 2006 eruption of Augustine Volcano, Alaska was accompanied by multiplets, however multiplets were not a dominant part of the seismicity, implying a low MPTS [Buurman and West, 2010]. Much like the 14 October eruption of Bezymianny, short–life span (minutes to 3+ days) multiplets were present before many of the explosions. When extrusion began, multiplet life spans became longer (>1 day), similar to the shift in life spans at Bezymianny. Dome extrusion did not include spines or slickensides, suggesting that the viscosity of magma within the conduit may be most analogous to the viscosity of magma within the conduit during the 1980–1986 MSH eruption prior to 1984.

[42] No single eruption has exactly the same multiplet characteristics, however taken in its entirety, several consistent characteristics stand out (Table 4). In particular, multiplet durations prior to and during unstable phases of eruptions were considerably shorter (hours) compared to multiplets during stable phases (days–weeks). Also, the variability of events within multiplets, comparable to the standard deviation at MSH and Bezymianny, was generally higher during unstable time periods than stable time periods.

4.4. Generalized Model

[43] To explain our observations, we propose a generalized model where an actively degassing and viscous plug within the shallow conduit will facilitate multiplet development and that the amplitude, standard deviation, life span and MPTS are a function of the stability of the conduit (Figure 12). Additionally, the viscosity of the magma within the conduit drives the prevalence of multiplets with respect to the overall seismicity (MPTS). Conceptually, as pressures and/or stresses increase within the conduit prior to an explosive event, the average amplitude and standard deviation of the multiplets increases while the MPTS and life spans tend to decrease. During periods of relatively low stress and/or pressures within the conduit (i.e., dome extrusion), average amplitudes and standard deviations are relatively low, while the duration and MPTS are relatively high. Qualitatively, a partially crystallized and actively degassing plug provides the environment most conducive to the generation of multiplets. The surface expression of such magma is often the extrusion of a spine or blocky lobe at the surface. If a viscous and degassing plug is present, multiplets may be generated by shear along the edges of the extruding plug [e.g., Neuberg et al., 2006, or failure of the viscous plug itself [e.g., Massol and Jaupart, 2009]]. Alternatively, the viscous state of the plug may facilitate the repeated flow of exsolved gases into cracks, creating earthquakes around the conduit [White et al., 1998; Tuffen et al., 2003; Molina et al., 2004].

[44] When the extrusion rate is too high to allow for decompressive crystallization and degassing (>1–3 × 10⁻⁴ m/s [Cashman et al., 2008]), multiplet development is less prevalent. Multiplets occurring deeper than 2 km, under a cooled and solidified cap, or when magma ascent is rapid (e.g., Bezymianny 2007, MSH post 18 May 1980–1982) could be related to gasses escaping out of the conduit into the country rock; however, without persistent cracking of a viscous plug to focus gas flow into the country rock, the generation of multiplets may not be as efficient. Low-frequency earthquakes in this setting are most likely from fluid-filled cracks [e.g., Chouet, 1996].

5. Conclusions

[45] Using continuous data to construct multiplet catalogs, we have identified several multiplet characteristics, particularly MPTS, that appear to correlate with changes in physical state of the shallow conduit and thus may be useful for constraining eruption types based on preeruptive seismicity. Multiplet development appears to be most efficient in the presence of a viscous degassing plug. The presence of a cold and dense plug, or hot low-viscosity magma at shallow depths, appears to result in the occurrence of few, if any multiplets. Common trends in amplitude, standard deviation and life span at MSH and Bezymianny volcanoes suggest that these characteristics may be an indicator of relative stability within conduit and thus could be useful for forecasts of explosions.

[46] Acknowledgments. The authors wish to thank the Kamchatkan Institute of Volcanology and Seismology and the Kamchatkan Branch of Geophysical Services for their assistance in installing the maintaining the seismic network at Bezymianny Volcano. Detailed reviews by Roger Denlinger, Seth Moran, Cynthia Gardner, Jackie Caplan-Auerbach, and Jean–Luc Got significantly improved the readability and content of the paper.

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