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SEISMIC SIGNALS AND SOURCES AT FUEGO VOLCANO, GUATEMALA
DURING JANUARY 2012

By

Kyle Arthur Brill

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

In Geophysics

MICHIGAN TECHNOLOGICAL UNIVERSITY

2019

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This dissertation has been approved in partial fulfillment of the requirements for the Degree of DOCTOR OF PHILOSOPHY in Geophysics.

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Dedication

To my family, for teaching me what that means.

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Preface

This document includes previously published materials and materials which are planned for submission to journals for publication.

Chapter 2. “Foundations for Forecasting: Defining Baseline Seismicity at Fuego Volcano, Guatemala” was published on 03 July, 2018 by *Frontiers in Earth Science* with the citation: “Brill KA, Waite GP and Chigna G (2018) Foundations for Forecasting: Defining Baseline Seismicity at Fuego Volcano, Guatemala. *Front. Earth Sci.* 6:87. doi: 10.3389/feart.2018.00087”. As stated in the Author Contributions section of the manuscript: “Gregory Waite, Kyle Brill, and Gustavo Chigna contributed to the conception and design of this work. Kyle Brill wrote the first draft of the manuscript, performed initial data processing for the temporary array, statistical analysis, and velocity modeling. Gregory Waite supervised all work, advised Kyle Brill on data processing methods and provided revisions for the manuscript. Gustavo Chigna facilitated access to Guatemalan field sites, performed initial data processing for the permanent station, gave insights to monitoring challenges and needs, and provided revisions for the manuscript. All authors read and approved the submitted manuscript.”

Chapter 3. “Characteristics of repeating long-period seismic events at Fuego volcano, January 2012” is in preparation for submission to the *Journal of Geophysical Research: Solid Earth*. The chapter was written by Kyle Brill under the supervision of Gregory Waite.

Chapter 4. “Continued variability of very long period seismicity at Fuego volcano, Guatemala as of January 2012” was created for this manuscript. The 2009 peak amplitudes from events with cross correlation values above 86.5% used in Figure 4-6 was provided by Gregory Waite, and the rest of the chapter was written by Kyle Brill under the supervision of Gregory Waite.

Chapter 5. “Long term stability of conduit dynamics at Fuego volcano, Guatemala, 2008-2015” was created for this manuscript, written by Kyle Brill under the supervision of Gregory Waite.

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I'll start by thanking my advisor, Dr. Greg Waite for telling me so many times that I could "definitely get it done this semester" when we met in week 1 and then for being so gracious in week 10 when we started making plans for postponing (again... and again...). I'm so excited that cycle might finally be ending, and so grateful and amazed that I never found the end of your patience. My committee members Dr. Wayne Pennington, Dr. Simon Carn and Dr. Matt Haney, have been incredible as well, especially through a rough qualifying exam and long periods of radio silence - I think a few more months and you might have been able to declare me legally dead. Your feedback and responses have always been encouraging and productive, despite whatever your current life and career circumstances were throwing at you.

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Abstract

Forecasting volcanic activity is challenging. The task is uniquely difficult at open vent volcanoes which present persistent low-level eruptions over long periods of time. Volcán de Fuego in Guatemala began its current eruptive episode in 1999. Fuego exhibited “background” levels of activity during January of 2012 when we installed a temporary monitoring network to produce a detailed baseline description of the volcano’s behavior. We accomplish this using data from two low-frequency microphone arrays, nine broadband (50 Hz to 30 second flat response) seismic stations, and visual time-lapse imagery collected over a period of ten days. We begin with a detailed description of all observed sources of seismicity including: both harmonic and non-harmonic tremor, rockfalls, a variety of signals associated with frequent small emissions from two vents, and many repeating, discrete, pulse-like long period (0.5–5Hz) events not linked to any visible emissions from the vents. We compute a 1D local velocity model and use it to generate preliminary locations of the different events. From there, we perform full waveform moment tensor inversions to better constrain the locations and the mechanisms for the repeating long period events. We find that the events are being generated by the opening and closing of an assortment of small, shallow, sub vertical cracks as those cracks pressurize, rupture, and release volcanic gases. Finally, we examine very-long period (10 – 60 second) signals associated with volcanic emissions and relate them to pressurization in the conduit prior to larger explosions. We propose that the volcanic vents at Fuego form caps of crystal rich magma which solidify near the top of each vent but above the location of the very-long period source. As new magma nears the top of a conduit and begins to degas, the cap fails at different points and to different degrees, generating the variety of emissions and seismic signals we observe. The insights gained from these investigations provide a better understanding of the dynamics of Fuego volcano during low points of activity and provide a baseline from which to study future activity at Fuego.

1 Introduction

Volcanic activity is responsible for the creation of beautiful landscapes, rich soils, and in the tropics, comfortable climates at higher altitudes in latitudes that would otherwise be stiflingly hot. It is not surprising therefore that intelligent human beings often find themselves living within areas that have been labeled by scientists as hazard zones. The majority of the time, these areas can be extremely pleasant and often profitable localities for human endeavors, and the risk posed by volcanic activity to life and livelihood can reasonably often be deemed acceptable. One of the most crucial points in these areas becomes a question of timing: when will the next eruption occur and will there be enough warning to get people and possessions to safety?

Responsibility for volcano monitoring efforts is most often assumed by government agencies for two main reasons. First, governments are the primary consumers of the information gained through monitoring of volcanoes as they are responsible for coordinating responses in emergency situations. Second, because the fruits of volcano monitoring are non-excludable (people who do not contribute to monitoring efforts still benefit from advanced warning of eruptive activity) and non-rivalrous (one person knowing about the present level of activity does not prevent other persons from using that information) the activity is by definition an example of a public good (Samuelson, 1954) and therefore is most effectively passed to governmental institutions. These institutions suffer afflictions common to many similar groups which provide public goods in that they must share limited resources to accomplish their directives and priorities are set by forces well outside the control of the institution itself.

The fact that making the most of scant resources is a prime consideration of institutions charged with protecting human life and property, combined with the steep credibility costs associated with false alarms means that the design and operation of monitoring systems is a high stakes game with dire consequences (Donovan & Oppenheimer, 2014). These challenges are compounded in economically weak areas where collective resources are already even more limited and individual households are more vulnerable to the hazards posed by volcanic unrest (Annen & Wagner, 2003). One of the only positive aspects to this paradigm is that it forces agencies rely on cooperation with other institutions with similar mandates and promotes open communication among the scientific communities investigating volcanic phenomena (for example, N.O.V.A.C., I.A.V.C.E.I., I.R.I.S., and V.D.A.P.).

Increased seismic activity is often one of the most obvious indicators of volcanic unrest (Tilling, 2008), and seismic monitoring of volcanic environments is therefore an essential component of any volcano observation endeavor. Over the last 30 years advances in the field of volcano seismology have been crucial to aiding the scientific understanding of the processes that precede large-scale volcanic eruptions. A small number of broadband seismic stations can be one of the most cost-effective means of basic volcano monitoring if the goal is to forecast large eruptions (RA White et al., 2011). Though these successes are indicative of the great strides the field has made, there is still much to be desired in

the medium-term accuracy and precision of eruption forecasting, especially when limited resources are available. Establishing a long, detailed and well understood baseline of eruptive activity levels is one way to facilitate more accurate medium-term forecasts, and can be especially valuable in open vent situations (Tilling, 2008).

Recent advances in instrumentation as well as data analytics have continued to reveal more and more detailed understanding of the inner workings of volcanic systems. The introduction of relatively inexpensive, portable, broadband seismometers has allowed us to observe seismic signals at new time scales, opening windows of understanding to different parts of the volcanic system. These measurements coupled with increasingly powerful computer processors and smarter algorithms have allowed seismologists to invert signals with periods between 2 to 100 seconds, termed Very-Long Period (VLP), to gain new insights into the physical processes involved in generating these seismic sources (Chouet & Dawson, 2013). These VLP signals have the advantage of not being affected by small scale heterogeneities within volcanic edifices which can contaminate signals at higher frequencies with jumbled path-effects. However, L. De Barros et al. (2011) demonstrated the importance of incorporating near-field measurements and effects in these inversions in order to fully understand the wave field. Signals with periods between 0.2 and 2 seconds, termed Long Period (LP) have long been associated with many different observed processes (i.e. fluid movement, resonance, etc.), but the ability to record these signals from multiple distances and azimuths around volcanoes has allowed greater insights and understanding of these processes. For example, Almendros and others (2012) show the importance of sampling in different radial directions around a volcanic source and describe some challenges that still need to be addressed. Many studies have also integrated other forms of data such as high speed video, thermal imaging, acoustic measurements, and tilt measurements to help constrain seismic sources based on these external observations (Johnson et al., 2008; Lyons & Waite, 2011; Nadeau et al., 2011; Scharff et al., 2014; Waite et al., 2013). The challenge now is to begin incorporating these recent insights into monitoring efforts, with an emphasis on gleaning the most information from the least additional investment. This dissertation will aim to advance this directive at Fuego Volcano in Guatemala, Central America.

1.1 Fuego volcano Background

Fuego volcano is one of the most persistently active vents which comprise the Central American Volcanic front, and at ~3800 m has represented the main center of activity of the approximately 80,000 year old Fuego-Acatenango massif for the past 8,500 years (Vallance et al., 2001). Activity from the Fuego vent has been chiefly basaltic-andesitic in composition, in contrast to the mostly andesitic activity of previous vents (Basset, 1996). Fuego has had more than 60 documented historical eruptions since 1524 (Escobar Wolf, 2013). The current eruptive episode began in 1999 and has been marked by periods of diffuse basaltic lava flows, strombolian style punctuated explosions and degassing events, and occasional paroxysmal events.

Constant activity and relatively easy access to the flanks of the volcano make Fuego an ideal location to study open vent volcanic behavior. Over the last 14 years, research teams at Michigan Technological University have collected diverse data sets with the help of the observatory staff and volcanology section by permission of the director of INSIVUMEH, mostly through field campaigns lasting from five to fifteen days during the local dry season lasting from November to April and supplemented with data collected by students working at OVFGO while serving in the U.S. Peace Corps as part of Michigan Tech's Peace Corps Master's International Program.

Publications generated by this partnership between INSIVUMEH and Michigan Technological University have described various eruptive phenomenon during this current eruption. Lyons et al. (2010) described an observed pattern of activity which occurred from 2005-2007. Lyons and Waite (2011) utilized VLP inversion to image part of the upper conduit system. Nadeau et al. (2011) imaged SO₂ plumes emitted by the volcano and corresponding seismic activity to propose a sealing mechanism in the upper conduit through rapid crystallization facilitated by Fuego magma's high water content which allows it to behave in a much more brittle fashion. Escobar Wolf (2013) mapped recent eruption products and used them to inform models of possible future scenarios and interpret prehistoric activity, used community interviews to assess perceptions of risk in communities around the volcano, and explored possibilities and requirements for the implementation of an early warning system around the volcano. Waite et al. (2013) examine different VLP signals which have been observed during various field campaigns over several years and explore the changes in style and possible causes for variability over time. Waite and Lanza (2016) further explored the source mechanism of the 2009 VLP by including the effects of tilt in the source inversion and employing a nonlinear inversion technique to better understand the mechanism results.

This dissertation will show how knowledge gained from relatively short-term field occupations can inform cost effective improvements to existing monitoring efforts in a manner that will be useful to those charged with day to day operations. I will primarily focus on data collected during January of 2012 but will leverage data from 2008 and 2009 for additional context. During the 2012 deployment, we occupied a total of 10 sites between 11 and 29 January and during that period recorded approximately 6 days of data with 9 stations running simultaneously. Seismic and acoustic data were recorded on RefTek 130 Data Acquisition Systems at 100 Hz. Two stations had collocated tilt-meters and two time-lapse cameras and one video camera recorded images of activity. A Forward-Looking Infrared Radiometer (FLIR) captured thermal images and we used a UV camera to capture images of the plume at higher wavelengths, but operational difficulties limit the application of these two hyperspectral imaging devices to qualitative analysis.

2 Foundations for Forecasting: Defining Baseline Seismicity at Fuego Volcano, Guatemala¹

2.1 Abstract

Accurate volcanic eruption forecasting is especially challenging at open vent volcanoes with persistent low levels of activity and relatively sparse permanent monitoring networks. We present a description of seismicity observed at Fuego volcano in Guatemala during January of 2012, a period representative of low-level, open-vent dynamics typical of the current eruptive period. We use this time to establish a baseline of activity from which to build more accurate forecasts. Seismicity consists of both harmonic and non-harmonic tremor, rockfalls, and a variety of signals associated with frequent small emissions from two vents. We categorize emissions into explosions and degassing events (each emitted from both vents), however the seismic signatures from these emissions are unique. We propose that both vents have conduits which partially to fully seal between explosions. We discuss how this model allows for the two types of emissions and accommodates unique seismic waveforms we recorded. In addition, there are many small discrete events not linked to eruptions that we examine in detail here. The discrete events include 5 families of repeating, pulse-like long period (0.5-5 Hz) events comprised of 183 individual events. Using arrival times from the 5 families and other high-quality events recorded on a temporary, nine-station network on the edifice of Fuego, we compute a 1-D velocity model and use it to locate earthquakes. The waveforms and shallow locations of the repeating families suggest that they are likely produced by rapid increases in gas pressure within a crack very near the surface, possibly within a sealed or partially sealed conduit. The framework from this study is a short but intense observation period, activity description, seismic event detection, velocity modeling, and repose period analysis. This framework can act as a template for augmenting monitoring efforts at other under-studied volcanoes. Even relatively limited studies can at a minimum aid in drawing parallels between volcanic systems and improve comparisons.

2.2 Introduction

Increased seismic activity is often the most discernable indicator of volcanic unrest (Tilling, 2008), and seismic monitoring of volcanic environments is therefore an essential component of any volcano observation endeavor. In many cases, the ascent of magma from the mid crust is signaled by swarms of earthquakes weeks or months prior to an explosive eruption (Randall White & McCausland, 2016). Over the last 30 years, advances in the field of volcano seismology have been crucial to aiding the scientific understanding of the processes that precede large-scale volcanic eruptions (Chouet & Matoza, 2013). Even a small number of broadband seismic stations can be one of the

¹ The material contained in this chapter was previously published in *Frontiers in Earth Science*

most cost effective means of basic volcano monitoring if the goal is to forecast large eruptions (RA White et al., 2011). Despite these successes and associated advances in the field, medium-term accuracy and precision of eruption forecasting still has much room for improvement.

Sometimes the beginning or ending of a volcanic eruption is not a discrete event. Eruptive episodes can persist over time scales from days to years, and in rare cases decades (Siebert et al., 2011). These “open-vent” volcanoes (Rose et al., 2013) – where connections between a magma body and the atmosphere are already established, or “quiescently active” (Stix, 2007) or “persistently restless” (Rodgers et al., 2013) volcanoes – where those connections open and close due to seemingly small changes within a system, provide opportunities for understanding volcanism as a phenomenon, but also present unique challenges for hazard mitigation (see Rose et al. (2013) for a review). When a volcano already exhibits frequent explosive eruptions, nearly continuous gas emission, and abundant volcanic seismicity, indicators that precede a shift to more dangerous levels of activity may be subtle (Roman et al., 2016). In these open systems, it is important to understand more detail about the seismicity to recognize changes in complex, low-level signals. Establishing a long, detailed, and well understood baseline of eruptive activity levels is one way to facilitate more accurate medium term forecasts (Tilling, 2008), and can be especially valuable in open vent situations (National Academies of Sciences, 2017).

Fuego volcano is one of the most persistently active vents in the Central American Volcanic front, and has represented the main center of activity for the approximately 80,000-year-old Fuego-Acatenango massif for the past 8,500 years (Vallance et al., 2001). Fuego lavas have been chiefly basaltic-andesitic in composition, in contrast to the mostly andesitic activity of previous eruptive centers (Basset, 1996). Fuego has had more than 60 documented historical eruptions since 1524 (Escobar Wolf, 2013). The current eruptive episode began in 1999 and has been marked by periods of basaltic lava flows, strombolian style explosions and degassing events, and occasional paroxysmal events with Volcano Explosivity Indexes (VEI) of 2 and below.

Constant activity and relatively easy access to the flanks of the volcano make Fuego an excellent location to study open vent volcanic behavior. A number of research groups have partnered with the Guatemalan Instituto Nacional de Sismologia, Vulcanologia, Meteorologia, e Hidrologia (INSIVUMEH) during this current eruptive episode to study the activity and work toward mitigating volcanic risk, with a large focus on using seismic and complementary data to characterize the magmatic system. A relatively long-term study by Lyons et al. (2010) used daily visual observations, seismic data, and thermal satellite images to characterize quasi-cyclic activity that included weeks to months of low-level explosive eruptions between paroxysmal eruptions that last for 1-2 days. Several field campaigns have collected data from a variety of sensors including seismometers, tilt meters, infrasound microphones, thermal imaging cameras, and SO₂ cameras to study explosive activity in more detail. Among the findings of these groups is the strong association between seismicity and gas emission. This includes intra explosion

non-harmonic tremor accompanying gas emissions (Nadeau et al., 2011) and three repeating very-long-period (VLP) event types associated with explosive ash-rich emissions from two separate vents and weaker puffing activity (Waite et al., 2013). The multi-instrumental work has led to a model for Fuego in which a seal in the uppermost conduit develops rapidly through microlite crystallization. Tilt data show that the sealed vent results in a pressurization and inflation of the summit beginning 20-30 minutes before most explosions (Lyons et al., 2012). Inversions of the seismic signals for the source of VLP events have produced a model for the uppermost conduit which dips slightly to the west below a pipe-like uppermost portion (Waite & Lanza, 2016).

This recent work has focused primarily on eruption-related seismic activity to shed light on the explosion processes, but no broad characterization of local volcano tectonic (VT) or long period (LP) seismicity has been undertaken since the eruptive episode of 1975-1977 (Mcnutt & Harlow, 1983; Yuan et al., 1984). In this study, we describe the seismic activity during January of 2012 with an emphasis on LP activity. Based on discussions with the INSIVUMEH staff and compared to activity observed before (i.e. Lyons (2011)) and since the field occupation (i.e. Global Volcanism Program (2013) and (Chigna et al., 2012)), the volcanic activity observed during this time represents a typical period between paroxysms and serves as a good example of background activity. This study describes the seismic activity during this time and highlights processes not previously investigated.

2.3 Methods

2.3.1 Instrumentation

We installed nine broadband seismometers around Fuego volcano from 11 January to 29 January 2012 (Figure 2-1) at distances between about 800 m and 3 km from the summit. Sites were chosen to provide full azimuthal coverage at distances as close as possible to the vent without compromising safety. Due to the steep topography and nearly continuous rockfall, the southern side of the edifice is less accessible than the north. Data were recorded on RefTek 130 Data Acquisition Systems at 100 Hz from seven Guralp CMG-40T (50 Hz to 30 s flat response) and two Trillium Compact (100 Hz to 120 s) seismometers. One of the Trillium Compact instruments was initially located at the N station site due to time constraints in the field and moved the following day to the NW1 site the following day for the remainder of the occupation. Two stations (NE1 and NW1) had collocated tilt-meters and arrays of three low-frequency microphones. Two time-lapse cameras located at ~800 and 1000 m NNE of the summit recorded images of volcanic activity and weather conditions. One of these cameras, a PlotwatcherPro made by Day6Outdoors, hereafter referred to as Cam1 captured images (1280 x 720 pixels) at 1 second intervals during daylight hours. The other, a Canon PowerShot A480 with a firmware modification, hereafter referred to as Cam2 recorded images (2272 x 1704 pixels) at 5 second intervals continuously (day and night) while battery power and storage space remained. Camera clocks were calibrated by hand, referencing hand-held

Figure 2-1. January 2012 locations and operational times of equipment. Part a) shows a map location of Fuego volcano in Guatemala. A larger-scale view of Fuego with the locations of the time-lapse cameras and seismic stations is shown in b). White triangles mark the location of the Trillium Compact instruments and black triangles indicate Guralp CMG-40T instruments. The black square represents the permanent short period FG3 station operated by INSIVUMEH. Cam1 and Cam2 mark the locations of the time-lapse cameras. The approximate location of the summit vent is shown in red and the approximate location of the flank vent is shown in orange. Contour intervals are 500 meters. The operational times of the stations and time-lapse cameras are shown in c).

GPS units, so the accuracy of image time stamps is assumed to be ± 1 second of true GPS time.

2.3.2 Event detection

We employed several methods to identify discrete events in the combined seismic, infrasound, and imagery data. This meant that our definition of what constituted an event was a somewhat fluid concept during the different stages of analysis. Initially, events were emissions that could be clearly identified with the camera images. The associated seismic signals were then analyzed and upon further inspection of the seismic data, events with similar seismic signals were identified. Many of these other events did not have associated clear visual records, either because the summit was obscured by clouds or because they simply did not produce emissions. We also found seismic signals associated with activity such as rockfall that was not clearly visible in the imagery data. The rest of this methods section will explain our use of multiple detection methods which allowed us to classify the different types of events discussed in section 3.

2.3.2.1 Visual identification

To begin our description of the activity, we sought to identify events and event timing visually, defining events as visible emissions from the volcano as the INSIVUMEH observers would in their daily reports. We identified 571 events using the images acquired by Cam1 and 225 events using the images acquired by Cam2, classifying them based on which vent they were emitted from, their initial speed, and the color and opacity of plume emissions during the day and based on incandescence at or above a vent position and incandescence of ejected material during the night. While this captured a large number of events, camera downtime and lack of visibility due to weather meant that most of the time period of the deployment was not recorded visually. In addition, atmospheric conditions above and around the crater produced condensation and or dust clouds which could closely mimic weak degassing emissions. Although great care was taken to exclude this type of event from the record, it is possible that some non-events were falsely identified as emission events.

We used seismic data (vertical velocity traces and FFT spectrograms with 1024 second windows) recorded at temporary station NE1 to verify the volcanic activity associated with each of the events in the catalog derived from the images. This allowed us to eliminate events picked visually from the images which did not also appear contemporaneously with seismic activity as well as to describe the events in terms of their seismic characteristics. Upon removing false identifications, combining the datasets, and removing duplicate events observed with both cameras, we are left with a total of 448 events observed during our field campaign, averaging 2-3 events per hour over 7 days of camera operation. However, this is most likely a gross underestimate because during those 7 days of camera operation, visibility was often limited or blocked due to atmospheric conditions. Quantifying an exact amount of time that visibility was limited is

impossible because night images can only be classified as cloud free if incandescence is visible, but a lack of incandescence could be due to cloud obstruction or a lack of activity. An inspection of most single hours of activity while the cameras were recording with full visibility suggests 6-10 events per hour would be a better estimate, especially if weak degassing events are considered.

2.3.2.2 STA/LTA algorithm

We used the seismic data to create a consistent catalog of seismic events during the deployment. The initial processing was done with Boulder Real Time Technologies Antelope 5.7 software. The data were processed using a short-time average/long-time average (STA/LTA) triggering algorithm using all seismic stations in the network. The algorithm was calibrated by comparing the number and duration of events detected to the visual activity observed on the time-lapse cameras. Data were first filtered from 1-25 Hz using a four-pole bandpass filter, and Root Mean Square averages were taken over 1 second (STA) and 9 second (LTA) windows with threshold ratios for detection at 2.5 times the signal to noise ratio. When more than five stations in the network trigger on the same event, it is added to a catalog. The five-station threshold effectively limits false detection of rockfalls as emission events, which tend to be very localized and not detected by stations on opposite flanks. Figure 2-2 summarizes the timing of the identified events by showing variation in events per hour, inter-event time, and event duration. The events with especially long durations, i.e. longer than 10 minutes are generated by volcanic tremor coinciding with other activity which prevents reaching the detection shutoff threshold of 2.2 times the signal to noise ratio (SNR).

Events in this catalog were then reviewed manually, resulting in a total of 1032 events detected on 5 or more stations through the occupation, an increase of 584 events from visual observations alone. Most of the events detected by the STA/LTA algorithms had emergent onsets which were very hard to discern. SNR has been found to be the main source of pick error for individual analysts (Zeiler & Velasco, 2009). Four members of our research group picked P-wave arrivals and determined pick uncertainties for 10 separate events from the middle of the dataset, and although some events have clear, impulsive arrivals, many also have arrivals which are much more ambiguous and therefore might not be reliable for earthquake location or velocity modeling. These results informed our decision to assign arrival weights to picks to reflect the impulsiveness of onset based on the analyst assigned pick uncertainty, which range from 0 to 3 for values less than 0.06, 0.15, 0.30, and 0.60 seconds respectively, and 4 for values greater than 0.60 seconds. For a first order approximation of event locations, we located these events using Antelope's dbgrassoc program which returns a location only if a detected event can be located within a user-specified grid and relies on the IASPEI91 (Kennett, 1991) crustal model. IASPEI91 gives a P-wave velocity of 5.8 km/sec for the first 20 km depth, and 6.5 km/sec from 20-35 km depth. The locations were later refined with a local 1D model as described below.

Figure 2-2. Six days of seismic activity identified by an STA/LTA algorithm while 9 network stations were all operational. Event spacing and Duration plots have y-axes with logarithmic scaling.

2.3.2.3 REDPy

The initial catalog of seismic events served as a starting point for further analysis. Recurring events, seismic events that have a similar mechanism and occur in roughly the same location, are common beneath volcanoes. In order to identify classes of these events, we used the Repeating Earthquake Detector in Python (REDPy) tool (Hotovec-Ellis & Jeffries, 2016). This detector begins by using an STA/LTA algorithm to identify event arrivals on different channels across a seismic network and stores events in a series of tables, just as with typical detection algorithms. The difference between REDPy and other tools is in the event association step. When enough stations or channels are triggered at once, an event is run through a series of cross-correlations in the frequency domain for comparison with other events in the catalog and assignment based on cross-correlation coefficient values.

A user can choose to manually delete events prior to analysis based on some criteria, such as erroneous triggers. The system stores both true events and those that the user flags as false events. Each newly detected event is compared with both groups of events. If a new event matches one previously defined as a false event, REDPy skips to the next event. If the new event does not correlate with any of the deleted events, the system writes that event to an “orphan” table, or an event without a currently identified “family” of other similar events.

As the program continues, REDPy looks at each good event in comparison with events in the “orphan” table to determine a cross-correlation coefficient. If a new event correlates with an “orphan” event above a user defined threshold on enough stations, those correlating events are moved from the "orphan" table and grouped as a "family." The system designates the first event as a “core” event and writes it to a representative events table, which becomes important in the next step. If a new event does not correlate with any events in the current “orphan” table, it is cross-correlated with all previously identified “core” events in the representative events table. If the new event then correlates with any “core” events above the threshold, it is added to that event’s family. If not, the new event is appended to the “orphan” table.

Clusters are defined using the Ordering Points to Identify the Clustering Structure (OPTICS) algorithm (Ankerst et al., 1999) which, in this usage, relies on correlation coefficients. In this implementation, an event only needs to correlate with one other event in the family to be included in the cluster; it favors fewer clusters with greater numbers of related events within each cluster family. At the same time, this algorithm identifies the event most closely correlated to all other events in the family and updates the representative event table accordingly. If the new event happens to correlate with more than one family, those family tables are merged without breaking OPTICS rules. Events are aligned within families after each clustering routine is completed so that correlation windows remain consistent.

Figure 2-3. Repeating earthquakes detected by REDPy. The grey lines in a-e represent the core event identified by the OPTICS algorithm for each cluster of events. The black line is a simple linear stack, and the red line is the phase weighted stack showing improved SNR. All the traces in the left section of each panel are of vertical components, and spectra are taken from the vertical component of NE1. Constituent waveforms are all filtered from 0.5-5 Hz with a 4 pole bandpass filter prior to any stacking, and each panel shows normalized traces. a) Cluster 1 b) Cluster 2 c) Cluster 3 d) Cluster 4 e) Cluster 5 f) Times for each event with cluster numbers on y axis and number of total events recorded to right of timeline (in cases where events overlap due to scale constraints, lighter shades signify more events).

Along with setting correlation thresholds, STA/LTA parameters, and minimum numbers of station or channel detections necessary to trigger the REDPy system, the user can search different frequency bands and give events on the “orphan” table expiration times after which they will no longer be compared to new events. We used the same STA and LTA window length settings for the STA/LTA algorithm that were used in the Antelope analysis, although the REDPy bandpass filter was in the LP band (0.5 – 5Hz). We experimented with multiple filter bandwidths and found that including signal below 0.5 Hz caused the algorithm to return events which were essentially correlated microseism, and including signal above 5 Hz returned almost no events due to scattering and attenuation of signals along the path, or minor variations in source processes evident only in the higher frequencies. The STA/LTA trigger ratio was 2.5 as before and a ratio of 2.2 triggered the end of the event. We restricted this analysis to only the six closest stations, excluding S, SE2, SW2 because including them again returned more correlated noise than events in the final REDPy catalog. This effective reduction of stations from 9 to 6 resulted in our choice to opt for only requiring that 4 of the 6 stations return concurrent detections to be considered for clustering. For an event to be associated with an event family required a correlation coefficient of 0.7 or greater on 3 or more stations.

The program detected 370 events in five cluster families which had more than five repeating events between January 15 and January 24. An additional 1867 events were found with the STA/LTA detector but were not well correlated with other events (Figure 2-3). Many different station configurations and STA/LTA settings were tested to optimize the detection of ‘true’ events, but most produced more correlated noise than true event clusters.

2.3.3 Phase-weighted stacking

To improve the signal to noise ratio for the event families detected by REDPy, we use the time-frequency phase-weighted stacking technique. This technique weights the stack by instantaneous frequency determined by the S transform allowing frequency-dependent time windowing (Pinnegar, 2005; Schimmel & Paulssen, 1997; Schimmel et al., 2011; Stockwell et al., 1996; Thurber et al., 2014). and shows significant SNR improvement (Figure 2-3). We pick arrivals from the resulting stacks using `Seis_Pick` (Verdon, 2012) and assign those arrivals to the origin time and location of each core event from REDPy. Subsequently, we remove the remaining family members from the Antelope catalog.

2.3.4 Velocity modeling and earthquake location

To better constrain the Antelope locations, we derive a 1-D velocity model by relocating events using VELEST (Kissling et al., 1994). We fix velocities below 9 km to values reported by Franco et al. (2009), assuming most of the activity to be concentrated within the edifice and considering the limitations on event depths based on the ~4 km aperture of the array we had deployed. Station corrections are set initially to zero but are inverted for in each iteration and carried through to subsequent steps. We only use a subset of high

quality events for the velocity modeling procedure due to the complexities inherent in exploring the model space with the simultaneous inversion for velocity and location. VELEST is able to use P-wave and S-wave arrival times, but allows modeling with only P-wave arrivals. Due to the assumed proximity of sources to receivers and the challenges in obtaining precise P-wave arrivals, we restrict our velocity modeling to P-waves only.

Our subset firstly includes the five phase-weighted stacks of clustered events (PWSCE). Next, we select high quality events from the Antelope database. To be considered high quality, the events need to fulfill three criteria: first, be located by Antelope closer to the summit than the furthest station, S1; second, be located by Antelope no deeper than 10 km below sea level; and third, have at least 6 stations with arrivals weighted 1 or 0. We exclude events already within the phase weighted stacks and are left with 60 events plus the five PWSCEs. Thirteen of these 60 events exhibit contemporaneous spikes on the infrasound channels normally indicating explosions, and these events are given an initial location at the top of the summit crater. This results in a starting set of 47 events with initial locations as determined by the Antelope locations, 13 events with locations fixed to the summit, and 5 PWSCEs with initial locations set to the surface directly under one of four reference stations.

For 17 events in the initial Antelope catalog, the seismic events not only exhibit contemporaneous spikes on the infrasound, but also occur within two seconds of the onset of emissions from the vent detected visually on one or both time-lapse cameras. We treat these events as shots within VELEST which allows us to constrain their locations without giving them a known origin time. This assumption may contribute a small error, however because shots are subject to selection criteria later in the process, we deem the approach to be appropriate. To these shots we add regional earthquakes detected with our network and contained in the International Seismological Centre On-line Bulletin (2016), again fixing location but not origin time. After subjecting these shots to the same selection criteria as the other events, we had 25 shots, 17 of which were fixed to the location of the summit vent.

Following the “recipe” of Kissling and others (1994) and using approaches similar to Clarke et al. (2009) and Hopp and Waite (2016), we explore the initial model space by trying 1000 different random initial velocity models for four different reference stations. Each of these models consisted of 10 possibly separate velocity layers. Programmatic constraints of VELEST require all seismic stations be within the first layer of the velocity model, so our layer boundaries are -4, -2, -.5, 1, 3, 5, 7, 9, 17, and 37 km depth. The final model has six layers spanning from 2 km above sea level to a depth of 9 km. The thickness and spacing of these layers represents the minimum number of layers able to accommodate the variations we observed in early trials that also minimizes the number layers with redundant velocities. Layers eight, nine, and ten which are below 9 km are fixed to the regional velocity model of Franco et al. (2009) which report velocities of 6.55 km/s from depths of 9 km to 17 km, 6.75 km/s from depths of 17km to 37 km, and 7.95 km/s below 37 km.

We constructed the random velocity models starting with layer 1 (uppermost) and layer 7. We first generated 1000 random numbers uniformly distributed between 0 and 1 using MATLAB's rand function. We established upper and lower velocity limits for this top layer between 0.6 km/s and 4 km/s, so we multiplied that vector of random numbers between 0 and 1 by 3.4 km/s and added 0.6 km/s to enforce our upper and lower bounds for the layer. We repeated this process for layer 7 with bounds set between 2 km/s and 6.55 km/s. We used the randomly determined velocities for layers 1 and 7 as a new constraint on layer 4, and for each model, generated another random number between 0 and 1 and multiplied it by the difference between velocities in layers 1 and 7. Layers 2 and 3 were then created by generating two random numbers, between 0 and 1, multiplying them by the difference between layers 1 and 4, and then sorted with the lower velocity always being assigned to the shallower layer. This last step was repeated for layers 5 and 6 using the difference between layers 4 and 7 to complete the seven varying layers of the new randomly generated velocity models.

Although Kissling and others recommend against using shots in the early stages of exploring the initial 1-D velocity model because of the large effect they can have on the results and because they only sample the shallowest velocity layer, we chose to include shots because we assume that most of the events we recorded are occurring in the shallowest two layers, especially due to the programmatic constraint that all stations must be located within the uppermost modeled layer. The models were run for ten iterations, or until the program failed to find a better solution after four tries. The best resulting model is selected as the model which minimizes both RMS error and station correction range.

The events are further refined for the next step by removing picks with residuals greater than 0.25 seconds. If this results in less than 6 picks for an event, the event is removed from the working catalog. Individual events with RMS greater than 1.0 or with station gaps of greater than 270° are also removed from the set. These criteria left 7 events plus 5 PWSCEs and 16 shots, 10 of which are explosions at the summit vent. These events pass through to another 1000 random velocity models, but incorporate the new station corrections, event locations, and event origin times. We again select the model with the lowest RMS error and minimum station corrections as the best resulting model. We then iteratively feed these results into VELEST simultaneous inversion mode until the velocity model and earthquake locations stabilize to have minimal changes from one iteration to the next. We run the events through VELEST single event mode to locate the earthquakes without simultaneously inverting for velocity. The final results in Figure 2-4 contain 7 events plus 5 PWSCEs with 14 shots (8 at the summit vent) which still meet the initial selection criteria.

Figure 2-4. a) Map of final locations of 5 PWSCEs (boxes and numbers), 7 other events (dots) and 14 shots (asterisk), all based on 1-D P-wave velocity model. Dark triangles represent stations with positive corrections, light triangles represent stations with negative corrections. b) North-South cross section through Fuego vent, sharing latitude coordinates with a. c) East-West cross section through Fuego vent, sharing longitude coordinates with a. d) 1-D velocity model e) Histogram of RMS errors for the events f) Corrections applied to each station in final 1D model.

Figure 2-5. Real-time Seismic Amplitude Measurement (RSAM) from station NE1(a) and FG3(b & c). Each sample in a and b is the mean amplitude of a 60s, non-overlapping window of data, high pass filtered at 1 Hz. Grey dashed lines are regional tectonic earthquakes, with associated numbers reporting RSAM values (in $\mu\text{m/sec}$ for NE1 and uncalibrated counts for FG3) and reported magnitudes of regional tectonic earthquakes. Dotted lines represent peaks generated by volcanic tremor and red line marks the largest observed explosion. Solid grey horizontal line represents an arbitrary cutoff value, below which individual peaks are not described in detail. c) plots the daily averaged RSAM from FG3 from January to September 2012. The green vertical bar represents the time periods captured in a and b.

2.4 Recorded activity

Fuego volcano, aside from being located on an overriding plate of a subduction zone is also situated relatively near the triple junction between the North American, Cocos, and Caribbean plates, which provides a large amount of tectonic activity to separate out from the volcanogenic seismicity in any seismic dataset collected at the site. From the 17th to the 23rd of January 2012, there were 75 magnitude 3.0 earthquakes and above within 5 radial degrees of Fuego's summit in the USGS Preliminary Determination of Epicenters (PDE) Bulletin (U.S. Geological Survey, 2017). Eight produce large peaks in real-time seismic amplitude measurements (RSAM) (Endo & Murray, 1991), and of the 34 individual measurements above 50 $\mu\text{m/s}$ on an RSAM plot produced from the vertical component of station NE1, only 13 are due to volcanic processes, twelve from two episodes of tremor, and one from an actual summit emission (Figure 2-5a). A similar plot of RSAM recorded on INSIVUMEH's permanent, short period station FG3 shows many of the same general features present in the record from the closer broadband instrument. Two differences stand out: first the much lower signal to noise ratio present at NE1, and second the much smaller contribution of tremor amplitudes (Figure 2-5b). Units are in counts for FG3 as we were not able to obtain an accurate instrument response for the permanent station.

2.4.1 Summit emissions

Emissions from the summit of Fuego are the most obvious and captivating activity we observed during our field occupation. There were different types of emissions from two active vents during the campaign; a "summit vent" and a "flank vent." Each vent exhibits impulsive onset, ash filled plumes, as well as emergent onset, ash poor plumes of white color (Figure 2-6). Signals from summit emissions are recorded across the temporary network and on FG3. Larger explosions show similar-shaped waveforms on all stations, but many even larger degassing events do not register at FG3 due to a generally lower signal to noise ratio at the farther station.

Even though the locations of these emissions appear spatially constant throughout our time in the field, the seismic waveforms generated by these explosions are very diverse. Inter-event times are very sporadic and do not show any correlation with amplitudes in the seismic or acoustic records, nor do plume type, location, or height from visual records. Some emissions have been linked to distinct types of very long period waveforms in previous work (Lyons & Waite, 2011; Nadeau et al., 2011; Waite & Lanza, 2016; Waite et al., 2013) and we continue to see these types of events in 2012. Further examination of these types of very long period events will be discussed in a future publication and is outside the scope of this current study.

Figure 2-6. Examples of summit emissions recorded at station NE1 plotted together with images from the time-lapse camera that was located near the seismic station. The spectrogram of the vertical component is plotted above the trace of the same time. The lowest trace is from a collocated infrasound sensor. Trace units are normalized. a) Summit Impulsive b) Flank Impulsive c) Summit Emergent d) Flank Emergent

2.4.2 Tremor

Volcanic tremor has been observed at many volcanoes worldwide and is a broad term covering seismic signals of sustained amplitudes (Chouet & Matoza, 2013; Konstantinou & Schlindwein, 2003). As noted above, tremor at Fuego makes the largest contributions to RSAM measurements of the volcanic processes we observed during our field campaign. We identify two types of tremor during the period of observation. First, broad band tremor with energy between 0.5 and 8 Hz occurs at different intervals throughout the dataset, lasting anywhere from two minutes to over an hour. Second, narrow band harmonic tremor with a fundamental frequency somewhere between 0.5 and 2 Hz with anywhere from three to eight overtones (Figure 2-7). Short, less than 100 second duration episodes are common, as well as episodes lasting longer than 30 minutes. Both long and short duration harmonic tremor exhibits non-stationary fundamental frequencies shifting as much as 2 Hz, easily identifiable by the strong gliding of overtone frequencies over time. Tremor is visible at the FG3 station, but with lower amplitudes than signals generated by other activity when compared with temporary network stations. Additionally, all but the first two overtones in episodes of harmonic tremor were absent, presumably due to attenuation of higher frequencies along the longer path to the short period station from the summit.

Figure 2-7. Examples of a) broadband tremor and b) harmonic tremor recorded at station NE1 plotted together with images from the time-lapse camera that was located near the seismic station. The spectrogram of the vertical component is plotted above the trace of the same time. The lowest trace is from a collocated infrasound sensor. Trace units are normalized.

Figure 2-8. Example of a rockfall recorded at station NE1 and SW1, and peak frequencies determined with FFT of events detected with STA/LTA algorithm at each station showing rockfall being detected on SW1 station.

The broadband and harmonic tremor episodes can happen immediately after an explosive event or emerge out of background signal independent of other activity, and other types of activity occur simultaneously with both classes of tremor as well. During several of the episodes of both types of tremor, we observe steady white, ash poor emissions from the summit vent. Flank vent emission is also possible, but not detectable due to the positioning of the cameras.

2.4.3 Rockfalls

Rockfalls are ubiquitous during the observation period, mostly originating near the crater rim and proceeding down the southern flanks to the barrancas below on the order of several episodes an hour. Due to the lack of an active lava flow front, most of the material is sourced from older cooling lava flow terminal edges near the summit or from precariously perched material from more recent explosive events from one of the two active summit vents. Smaller rockfalls initiate at seemingly random intervals due to instability inherent in the location of the source materials, but most of the largest rockfalls take place soon after explosive events being apparently dislodged. These rockfalls posed a significant hazard to personnel during our field campaign and aside from the terrain itself proved the second largest limiting factor in where stations were ultimately located during the occupation.

The fact that most rockfalls occurred to the southwest meant that our time lapse cameras did not capture any good examples of this type of activity. The rockfalls are easily distinguishable in the seismic records though due to the frequency content being almost exclusively above 10 Hz which distinguishes rockfalls from tremor, the emergent onset of the events followed by a ringing coda, a lack of infrasound signal, and the much larger amplitudes of the events on the stations located to the south (Figure 2-8). The choice of requiring 5 stations to simultaneously trigger to add an event to the catalog was also determined specifically to avoid detecting large amplitude rockfalls. Rockfalls are visible on the FG3 station, but most of the rockfalls activity while the temporary network was operating took place down the southwest flank away from the FG3 station and is therefore difficult to distinguish at FG3 from background signals without a simultaneous examination of the network stations.

2.4.4 Phase-weighted stacks of clustered events

Repeating seismic events in volcanic settings can highlight important physical processes. Interestingly, each of the PWSCEs show distinct signal characteristics (Figure 2-3), and none of the events within the stacks correspond with any type of consistent concurrent observed surface activity. We demean, apply a cosine taper, and apply a two pole, 0.5-5 Hz Butterworth filter forward and backwards (effectively creating a four pole filter) to each signal, and then demean again each detected event in a cluster before creating the phase-weighted stack. In each of the events, the southern stations show markedly lower amplitude signals and later onsets when compared to signals recorded on the northern

Figure 2-9. a) Top Row - PWSCE1 traces. Middle Row - Zoom-in of stacked signal onset. Bottom row - Spectrogram (5.12 second sample Parzen window with 80% overlap and 512 point nfft) of PWSCE1. b) Top Row - PWSCE2 traces. Middle Row - Zoom-in of stacked signal onset. Bottom row - Spectrogram (5.12 second sample Parzen window with 80% overlap and 512 point nfft) of PWSCE2.

portion of the temporary network, which is consistent with the events occurring near the vent.

2.4.4.1 PWSCE1

The first cluster contains 96 separate events (Figure 2-9a). The stack shows a small amplitude positive vertical first motion and negative first motion in the radial direction on all stations where a clear first motion is observable. On the NE1 and NW1 stations, a larger amplitude pulse follows for two cycles, and these cycles are identifiable on the SE1 and SW1 stations with much weaker amplitudes. The event shows high energy from 0.5-4 Hz at the onset and tapers down to 1-3 Hz after the first two seconds.

2.4.4.2 PWSCE2

The second cluster contains 22 separate events (Figure 2-9b). Low amplitude positive vertical motions precede a strong negative vertical motion at the onset of the event along with pulses away from the vent on the horizontal channels. The NW1 and NE1 stations record three similar cycles which are obscured and have a longer duration and almost ringing coda on the southern stations. All stations record a 1 Hz signal immediately prior to the main large amplitude signal which then extends from 0.5-3 Hz lasting 30 seconds.

2.4.4.3 PWSCE3

The third cluster contains 44 separate events (Figure 2-10a). The event shows a small amplitude positive first motion on all vertical channels as well as first motions away from the vent on the horizontal channels with several higher amplitude cycles following on all channels. A 1 Hz signal persists through the event and leads the main body of the signal which is distributed from 1.5-3 Hz, with much less energy below 1.5 Hz.

2.4.4.4 PWSCE4

The fourth cluster contains 7 separate events (Figure 2-10b). The beginning of this signal stack is quite noisy on the NW1 vertical station, and the signal stack is more emergent in nature which makes selecting a clear first motion in any direction difficult. The clearest station is the NE1, and that first arrival is small amplitude positive in the vertical direction. This same pulse can be matched on the NW1 station, with the horizontal channels showing a direction away from the vent at the same time. The spectrograms of the event on the different network station show the main energy arriving several seconds later at the southern stations compared with the northern ones, despite similar onset times in general. The spectrograms also show signal energy from below 0.5 to over 5 Hz despite the bandpass filter having been applied to each constituent of the stack.

Figure 2-10. a) Top Row - PWSCE3 traces. Middle Row - Zoom-in of stacked signal onset. Bottom row - Spectrogram (512 sample window with 80% overlap) of PWSCE3. b) Top Row - PWSCE4 traces. Middle Row - Zoom-in of stacked signal onset. Bottom row - Spectrogram (512 sample window with 80% overlap) of PWSCE4.

Figure 2-11. Top Row - PWSCE5 traces. Middle Row - Zoom-in of stacked signal onset. Bottom row - Spectrogram (512 sample window with 80% overlap) of PWSCE5.

2.4.4.5 PWSCE5

The fifth cluster contains 14 separate events (Figure 2-11). This signal is the most emergent of all the stacks, and as such was also the hardest to pick a clear first arrival or true first motion polarity. The event appears to have a small amplitude packet of energy appearing on all the stations. Unfortunately, upon closer inspection of the member events, this early signal does not appear to be consistent across all the events but rather a contaminating feature from one event. The spectrogram shows a strong band of energy at about 0.5 Hz for the duration of the event, with energy distributed through 4 Hz, and showing another brief peak of energy near 2.5 Hz lasting only 3 or 4 seconds.

2.5 Discussion

2.5.1 Velocity modeling

We make full use of the user controls allowed by VELEST to ensure that we arrive at a true minimum 1-D velocity model as defined by Kissling et al. (1994). We vary model damping parameters systematically for station correction, velocity, and earthquake locations and find the results are comparable over a wide range of parameters. Changing the reference station does not appreciably change the relative corrections between stations in the network, instead only shifting absolute values. For example, if we choose the station which observes most arrivals first or last as the reference station, all other network station corrections are positive or negative respectively. If we choose the reference station as a station observing arrivals somewhere after and before other stations

in the network, the station corrections distribute more evenly between negative and positive. The variations between modeled velocities of the top model layer reflects the effect of these shifts.

The station corrections we see make sense in the geologic context of Fuego with the stations to the north generally showing negative corrections and therefore faster velocities. We expect this material to be older and to have survived at least one hypothesized edifice collapse (Chesner & Halsor, 1997), meaning it should be physically more compacted and coherent than material to the south. The NE1 station seems to be particularly fast, but despite looking at various events for possible miss-picks, arrivals do seem to reach this station consistently earlier than others in the network. The variability of material that we had to dig through during station installation would lead us to expect some site effect differences, but the large variability between adjacent stations must be reflecting a very complex three-dimensional velocity structure that we can only hope to approximate with a minimum 1-D model.

In our early runs, we saw velocities in the upper layers consistently falling to nearly 300 ms^{-1} whilst reporting station correction factors above 5 seconds. Adding shots as model inputs keeps velocities in the upper layers of the model higher, and more geologically plausible. The lack of consistently clear arrivals for input to VELEST is the greatest obstacle to minimizing error in event locations, as very few events have sufficiently clear arrivals to pick on all nine stations in the temporary network.

2.5.2 Event locations and network resolution

The event locations we report above must be understood in the context of the errors propagated along with the modeling procedure. Hypocenter location errors for each event located with VELEST single event mode are between 110 m and 480 m despite selecting only the most reliable events. We therefore turn to different parts of the modeling process to give us information on how reliable the locations of each earthquake might be, such as tracking the earthquake locations throughout the modeling process.

Events show general trends throughout the modeling procedure. For instance, events which locate in the center of the network in the final model consistently end up in the center of the network with very little variation in the horizontal or the vertical directions. Events which show strong impulsive infrasound signals associated with explosive events but not captured on any of the time-lapse cameras are given a starting location directly below the summit vent, but at 0 m of elevation, which due to Antelope's lack of topography indicated the surface. These events migrated successively closer to the top of the topography at each step of the velocity modeling, indicating a trend to stable locations near the top of the cone.

The only events with an azimuthal gap greater than 180° that we did not eliminate from the data set through all phases of velocity modeling were the PWSCEs, which consistently locate closer to the north stations of the network. Because no consistent

surface activity occurs in the time-lapse images one minute before and three minutes after those arrival times, we believe that these repeating events are being generated by subsurface processes not previously observed. However, the lack of any observed activity in this area at Fuego in the years following our field campaign, along with the large arrival timing errors leads us to doubt the accuracy of these locations, which we infer to be restricted to Fuego's active cone.

We gain critical insight to the model space by selecting for our updated a-priori 1-D model one which minimizes both the RMS error of the run as well as the lowest average station corrections for all nine stations. In early runs, the events consistently locate much shallower in the cone, and stayed closer to the vent. Station corrections are much more reasonable with a full network spread around three tenths of a second as opposed to almost a whole second with the initial method of only minimizing RMS of the model. Solutions also stabilize more quickly and show less variability based on the initial reference station. This change greatly increases our confidence in the velocity model reported in Figure 2-4, even if the locations are still not accurate beyond restricting event locations to within the cone.

Two single events which were well constrained from Antelope still located north of the network, and despite the persistence of these locations, the temporary network could not

Figure 2-12 The top portion of the figure shows the vertical traces of the phase-weighted stack for event cluster 1 at four stations (distances are from station to summit vent) with the P and possible SV wave arrivals highlighted in solid black, the green and the red highlight the down going swing and following cycle of the dominant Rayleigh wave, while the bottom of the figure shows polar plots of particle motion normalized to the maximum amplitude of each trace at each station, showing the retrograde motion.

confidently constrain them. The last reported activity in the Acatenango portion of the massif was a series of phreatic eruptions which occurred in 1972 (Vallance et al., 2001), so seismic activity would not be unthinkable. Given the level of tourist activity on Acatenango, even a minor episode would potentially pose a risk to the dozens of people hiking the volcano on any given day. Differentiating these signals from other events in the Fuego vicinity would be even more difficult given that the whole complex is only continuously monitored by one short period station operated by INSIVUMEH. These events may occur deeper in the system but the depths cannot be constrained due to limitations in the temporary stations network aperture, and unmodeled complexity in the true three-dimensional velocity structure.

The five groups of similar events are likely driven by similar sources, although their waveform characteristics are quite different. The particle motions of the main amplitude pulse from the dominant cluster, PWSCE1, shows distinctly retrograde motion (Figure 2-12) indicating a prominent Rayleigh wave arrival. The shallow location of this event, coupled with the pulse-like signal which decays further from the vent and lower frequency content of the main pulse are remarkably similar to shallow events recorded at Mount Etna, Turrialba, and Ubinas (Bean et al., 2014; Chouet & Dawson, 2016). While we were unable to reliably model this event given the relatively large distance to the nearest stations south of summit, the similarity of the waveforms to those of the well-modeled events at Etna suggests these repeating events likely result from a similar mechanism. Given that Chouet and Dawson (2016) favor fluid-driven sources over a slow rupture dislocations due to better cross-correlation values between recorded data and generated synthetics, we interpret this as a rapid increase in gas pressure within a crack very near the surface. The other event clusters did not have the same dominant Rayleigh wave pulse but their locations within the cone suggest a gas or magma-driven process. However, the short observation period and lack of drastic changes in activity do not allow us to test for temporal evolution of events which would be predicted in a slow brittle failure of poorly consolidated volcanic rock (Bean et al., 2014), again limiting the strength of our conclusions.

It should be noted that we tried to identify events from the time windows around the phase-weighted stacks of events on the FG3 short period station operated by INSIVUMEH (Figure 2-1), but the low signal to noise ratio at the recording site made positive event identification impossible even in the stacked data. Adding arrivals from this station would have significantly increased our network aperture and the accuracy of deep earthquake locations, but for the velocity modeling section of this study the recordings at FG3 did not provide any helpful information.

While the occurrence of families of small seismic events suggests repetitive processes, another result this investigation highlights is the complexity of the explosions themselves. As noted above, similar surficial expressions exhibit markedly different seismic signatures. One explanation for this scenario would be that the conduit seals or partially seals between eruptions. Differences in the structure of each seal, how the seal forms, and where and how dramatically the seal fails would all produce different waveforms despite

similar locations and otherwise constant inputs from the broader system. Our observations support the eruption mechanism proposed by Nadeau et al. (2011) of a crystal rich mush solidifying and capping the vent, allowing pressures to build until the cap fails mechanically and allows material to escape.

Finally, we attempt to classify seismic events which are associated with explosions and differentiate them from those which are not. Interestingly, none of the events show distinguishing characteristics in frequency content, duration, or impulsiveness of onset; they only differ substantially in whether or not they have an accompanying infrasound signal. But unfortunately, even the presence of an infrasound signal is not always a reliable indicator of strictly subsurface activity as several observed events with varying plume volumes occurred without measured acoustic signals.

2.5.3 Repose period analysis

The details of individual events such as their locations and waveform characteristics can provide information about the processes responsible. Similarly, a detailed catalog of seismicity can be used to illuminate driving processes more broadly through relatively simple statistics. Varley and others (2006) apply statistical time-series analysis to volcanic activity at Colima, Tungurahua, Karymsky, and Mt. Erebus volcanoes. The authors show that different periods of activity can be distinguished by the distributions of the repose periods between events and event types. Data are classified as stationary or showing periodicity, clustering, or a trend, which points to events governed by constant processes independent of time or the competition between different processes. If each interval is independent of the one preceding it, the distribution of interval times is exponential and the governing processes in Poissonian in nature. One way to test for Poisson processes is to calculate the coefficient of variation, which is the standard deviation of the time between events σ_τ , divided by the mean interevent time $\bar{\tau}$, or $C_v = \frac{\sigma_\tau}{\bar{\tau}}$.

The governing process is Poissonian if $C_v = 1$ and clustered if $C_v > 1$. We calculate these values from interevent times from several sources which can be found in Table 2-1. Most of the measures of C_v are slightly greater than 1, and like Varley et al. (2006), we report lower coefficients of variation in subdivided event families. Differences in C_v imply distinct processes driving the activity, we see the largest difference when separating events by vent of origin or type of event (explosive vs. degassing). Degassing events in our dataset appear Poissonian and explosive events appear clustered. This fits well with a model of constantly degassing magma (Andres et al., 1993; Lyons, 2011; Nadeau et al., 2011; Rodríguez et al., 2004; Waite et al., 2013). However, the relatively short observation period, and therefore small sample number limits our ability to report distributions with any confidence. Increasing the catalog size would help to provide more confident interpretations in the future.

Table 2-1. The mean, standard deviation, and coefficient of variation of the lengths of inter-event times. All times are from the start of first event to the start of next event. The top two rows are seismic arrival times for events detected on five or more stations in the network. Antelope Origins are event origin times as determined by Antelope's dbgrassoc program using the iasp91 velocity model. NE1 Arrivals are human picked event arrival times from station NE1. Remaining rows are seismic arrival times on station NE1 of visually observed events and subsets thereof.

Source of Times	Events	$\bar{\tau}$	σ_{τ}	C_v
		hh:mm:ss.sss	hh:mm:ss.sss	
Antelope Origins	929	00:12:07.309	00:14:34.190	1.201952
NE1 Arrivals	936	00:12:13.600	00:14:50.049	1.213263
Visual Events	448	00:14:28.208	00:17:34.419	1.214477
Summit Events	333	00:21:02.250	00:31:11.036	1.482303
Flank Events	102	00:44:31.845	00:52:08.882	1.171057
Explosive Events	277	00:19:16.383	00:23:53.000	1.239154
Degassing Events	108	00:31:44.254	00:31:57.489	1.006951
Summit Explosions	95	00:26:18.000	00:33:58.000	1.291190
Summit Degassing	84	00:35:01.697	00:31:56.294	0.911784
Flank Explosions	69	00:45:48.000	00:55:29.999	1.211767
Flank Degassing	13	01:24:50.824	01:18:12.434	0.921744
PWSCE1	96	01:46:40.672	02:31:26.255	1.419578

Further investigation of the types of governing processes active at Fuego during periods of background activity through time lapse imagery and seismic event timing from computationally cheap algorithms can extend the analysis to periods of years. For example, recent work by Castro-Escobar (Castro-Escobar, 2017) showed that Fuego's paroxysmal eruptions are statistically independent in time, suggesting that the system recovers to a background state between each eruption. This makes understanding the characteristics of that background state all the more important.

2.5.4 A foundation for improved eruption forecasting

This analysis provides an example of the important information that is useful for starting the process of eruption forecasting. Many volcanoes throughout the world are monitored by one or fewer stations, and while monitoring agencies are adept at using minimal amounts of data to keep local populations safe, it is clear that a better understanding of the monitoring data should yield better forecasts. Ketner and Power (2013) show an example of how close examination of seismicity recorded on a single station during Redoubt volcano's 2009 eruption can provide a richer understanding of the progression of an eruptive event.

In the case of Fuego volcano, INSIVUMEH relies on observers who live on the volcano's flanks together with real-time seismic data from a short-period station about 6 km southeast of the summit. Fuego's larger 'paroxysmal eruptions' can produce pyroclastic

density currents that threaten nearby population centers and ash clouds that threaten aircraft. While INSIVUMEH has been successful using this approach, we sought to provide more detail that could be incorporated into a better understanding of the volcano in the future. Being able to compare contemporaneously recorded signals at FG3 and a network of stations closer to the vent clarifies the sources of some of the more striking features and increases confidence in classifying activity as an explosion or local rockfalls. It also sheds light on information missing from this record, which could aid in interpreting increases in activity prior to paroxysmal activity.

In cases where only a single station is responsible for monitoring an entire volcano, insights from temporary instrument deployments can shed light on signals recorded at the permanent station and clarify sources of ambiguous signals. Rodgers et al. (2015) provide an example at Telica volcano in Nicaragua of using seismic records and eruption observations to classify activity as belonging to either stable (permitting open-system degassing) or unstable (where open-system degassing cannot be maintained) phases. This example highlights an instance where low levels of seismicity, normally associated with quiescence can in some cases portend more dangerous activity. In cases where no permanent monitoring happens, temporary deployments during periods of quiescence can provide a baseline for comparison if activity later increases and requires further study to determine if that increased activity could become hazardous.

2.6 Conclusions

Our proposed template for a temporary monitoring network starts with selecting sites to ensure adequate radial coverage around a volcano. Visual observations recorded by time lapse cameras help aid later interpretation. Ideally, the observation period is as long as possible, but even a short time can be leveraged for deeper understanding. Data analysis should begin with classifying different types of emissions, if any, and identifying signals which do not manifest as surface activity. Utilizing a pattern identification algorithm, in our case, REDPy, and identifying a 1-D velocity model can be quickly and easily done following our methods.

Several results are reported. First, by classifying local seismic signals based on observed surface activity, we can be more confident in knowing what is happening on the volcano even when visibility is poor. Second, we have identified repeating events not directly tied to surface activity which is evidence that the volcanic plumbing system includes some level of complexity which should be further investigated. Third, despite the difficulties of constraining exact arrivals for most events in our catalog, we identify a reasonable 1-D velocity model which can itself serve as a starting point for future analysis, and we can be more confident in this model due to the exhaustive analysis done to produce it.

This work provides examples of analytical operations which can help to establish baseline levels of activity at open vent volcanic systems. The challenge with these systems from a monitoring standpoint is that precisely because of their relatively low levels of activity, forecasting changes in activity often comes down to paying attention to

small details and how they relate to one another. Without a baseline to compare to, forecasting can never be more helpful than simply guessing based on experiences at other volcanoes.

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3 Characteristics of repeating long-period seismic events at Fuego volcano, January 2012²

3.1 Abstract

We describe a suite of repeating long-period seismic events recorded on a temporary network over a period of 8 days during January 2012 at Fuego volcano in Guatemala. These events do not generally occur with explosions or other visibly or audibly detectable emissions from the volcano. Events are separated into distinct families based on different correlation coefficient thresholds. A correlation coefficient threshold of 70% for an individual event to correlate with at least one other event in the group yields two families with 123 events in the first family and 25 events in the second family. These two event families share common features so that if the correlation coefficient threshold is 65%, the families merge, and an additional 226 events are also included. The second event family, in which all the individual events present with low coda energies with short durations, frequency content concentrated below 2 Hz, and high signal to noise ratios, is used to create a phase-weighted stack. This phase-weighted stack is then inverted for source mechanism and location using unconstrained full-waveform moment-tensor inversion. The eigenvalue decompositions of the best fit locations indicate that the source is best represented by a crack with some volume change. The short duration of the modeled source time function and the slight variability of signal shape within the suite of repeating events indicate the observed events are likely caused by the rapid pressurization of cracks or series of connected cracks. The inter-event times of these events appear to be clustered, indicating driving processes more complex than continual degassing of magma in the conduit would allow. Better understanding of these events may shed light on processes not captured by real-time seismic amplitude measurements or gas flux measurements alone.

3.2 Plain Language Summary

In January of 2012, we recorded hundreds of small seismic events happening near the summit of Fuego volcano in Guatemala that were very similar to one another. For this to happen the events must be occurring in approximately the same place and the motions of the constituent parts time after time must be the same or very similar. Understanding what causes these special events tells us important information about what is happening in the volcano. The challenge is that volcanoes are made up of solid as well as molten rock arranged in complex ways. The complex paths that these seismic waves travel between their points of origin and the seismometers we use to record them produce seismograms which very difficult to interpret. Despite these challenges, we think we have enough background information to be confident that these events we recorded are

² The material in this chapter is in preparation for submission to the *Journal of Geophysical Research: Solid Earth*

happening when gas from the rising magma enters preexisting cracks or networks of cracks, pressurizes those cracks, and is then released. The timing of these events doesn't suggest that the constant degassing of the rising magma is the only driving process behind these events, and perhaps if we keep studying these repeating events, we might be able to better understand changes in the volcanic system.

3.3 Introduction

Volcanoes are responsible for dynamic geologic processes that directly impact human activity in their vicinity. These processes occur on timescales measured by units from milliseconds to millennia. Long period (0.5 - 5 Hz) seismic signals provide a window into this complexity. The sources of these LP signals are attributed to the movement of fluid, the resonance of fluid-filled bodies, or slow-moving brittle failure of volcanic rock; each with different implications for the volcanic systems in which they occur (for a review, see Chouet and Matoza (2013)). Confounding factors such as non-volcanic sources of LP seismic energy as well as difficulties discerning which processes or path effects may be responsible for an individual volcano's LP signals mean that locating and studying these sources over time can be as challenging as it is necessary to understanding the volcanic systems as a whole (e.g. Bean et al. (2014) and Chouet and Dawson (2016)).

Full waveform inversion is the primary tool for revealing the source processes from recorded seismicity at volcanoes, but this technique is limited by the large number of unknown elements usually present in volcanic environments. Many studies acknowledge these limitations and attempt to quantify the effects different unknowns have on the inherently non-unique results produced by these usually underdetermined inverse problems (Bean et al., 2008; Louis De Barros et al., 2013; Lanza & Waite, 2018a; O'Brien & Bean, 2009; Trovato et al., 2016). The first obstacle to overcome in most volcanic environments is usually a poorly understood velocity model. Different approaches have been employed in circumventing this obstacle: avoiding higher frequency bands where complex velocity heterogeneities cannot be sufficiently homogenized; utilizing other a priori information to account for deficiencies in velocity model details; or declaring complex three-dimensional velocity models unknowable and proceeding by testing model sensitivities. Trovato et al. (2016) explores the challenges of quantifying the influence of velocity models on the shallow LP events and recommends shallow LP events be located independently of an inversion procedure and then constrained inversions be utilized for determining source mechanisms. Lanza and Waite (2018a) look at result sensitivity to seismic network geometries and agree with earlier studies like Dawson et al. (2011) as to the amount and radial distribution of stations required to achieve acceptable results for retrieved source processes. When care is taken, waveform inversions of LP data can reveal details about the eruption process and conditions near the conduit (Kumagai et al., 2005; Lanza & Waite, 2018b; Matoza et al., 2015).

In January of 2012, we installed a 9-station temporary network of broadband seismometers to better understand low-frequency signals previously observed at Fuego

Figure 3-1. a) Locations of stations used for inversion on contour map of Fuego volcano (contour interval is 100 m). The light blue box outlines the volume of synthetic sources. Self-normalized particle motions for phase-weighted stacks of repeating LP event 1 and 2 are plotted in red and blue respectively and separated from the actual station locations for clarity. b) Location of Fuego within Guatemala. c) and d) show self-normalized vertical components of the phase-weighted stacks of repeating LP events 1 and 2 recorded at different network stations in red and blue respectively, with black lines in each panel representing linear stacks. The frequency spectra are taken from the NE1 station vertical component shown and are also self-normalized.

volcano in Guatemala. Several studies have used waveform inversion methods to identify source mechanisms for Very Long Period (VLP: 100-10 seconds) events at Fuego Volcano (Lyons & Waite, 2011; Lyons et al., 2012; Nadeau et al., 2011; Waite & Lanza, 2016; Waite et al., 2013), but LP seismicity has not been explored in depth. Here we examine families of repeating LP events from 2012 and compare them to data collected in 2008 and 2009.

3.4 Materials and Methods

3.4.1 Temporary seismic network

A temporary network of nine broadband seismometers (Figure 3-1) recorded data for approximately seven days in January 2012. Two stations, NE1 and NW1 had Trillium Compact instruments with flat response from 120 seconds to 100 Hz and the rest had CMG40T instruments with flat response from 30 seconds to 50 Hz. All stations recorded data on RefTek 130 Data Acquisition Systems at 100 samples per second. Stations NE1 and NW1 also had collocated arrays of three low-frequency microphones recording at the same sample rate. For further information about network configuration and full operational times, see Brill et al. (2018).

3.4.2 Event Detection with REDPy

REDPy (Repeating Earthquake Detector in Python) (Hotovec-Ellis & Jeffries, 2016) is a program for detecting repeating earthquakes in a dataset. The program uses a STA/LTA algorithm to detect events, and cross-correlates with other detected events. If the event correlates above a user defined threshold, it is saved as part of a family, otherwise it is saved as an orphan event. As the program continues detecting events, they are classified as part of families or compared to other events within the orphan group, and if a match is found within the other orphans, a new family is assigned. In this way, the program does not require predefined templates to be provided a priori. The family member which correlates best to all other family members is selected as the core event for each family.

We used REDPy to identify events from our dataset in the band 0.5-5 Hz. The long-term average window was set to 9 seconds and the short-term average window was set to 1 second. The STA/LTA ratio to turn on a trigger was 2.5 and 2.2 to turn that trigger off, and concurrent detections were required on 4 of the 6 stations processed. Different station configurations or STA/LTA settings were tested but produced more correlated noise than true event families. Each detected event was then compared to other events previously detected by REDPy, and if a given event correlated above a set threshold on a given number of stations those events were grouped into a family of events. The families of events that we detected in the 0.5-5 Hz band are described in detail in Brill et al. (2018) and had a minimum correlation threshold of 70% on three stations. The frequency content and signal durations of event families 3, 4, and 5 from Brill et al. (2018) make further analysis of these events using our present methods untenable. This leaves two event families suitable for further analysis. Self-normalized particle motions of phase-weighted stacks from each of these two event families are shown in map view in Figure 3-1a, and the stacked waveforms for these two event families are shown for the closest 6 stations in Figure 3-1c and Figure 3-1d. When visual observations were available, no event in either of the two remaining event families corresponded to any detectable emission from the volcano.

3.4.3 SNR reduction with tf-PWS and Velocity Model Station Corrections

We used the timing of events detected by REDPy to create waveform objects in GISMO (Reyes & Thompson, 2016) from all our channels on the network. For consistency in the inversions, we demeaned each trace and filtered it between 0.5 and 5 Hz, and then cross correlated all the traces in the time domain and shifted them per their lag for a linear stack. To further improve signal-to-noise ratios, we then created time-frequency domain phase-weighted stacks (tf-PWS) utilizing the S-transform (Pinnegar, 2005; Schimmel & Paulssen, 1997; Schimmel et al., 2011; Stockwell et al., 1996; Thurber et al., 2014).

Before passing to the inversion phase of our analysis, we applied a cosine taper to outer 25% of the tf-PWSs and pad them with more zeros out to 8192 samples. Several studies have investigated the problem posed by complex velocity structures in volcanic environments (Richardson & Waite, 2013; Trovato et al., 2016). The short operation time of our network does not lend itself to tomography studies, but the 1-D velocity modeling carried out in Brill et al. (2018) includes station corrections reported for each station in the network to compensate for unknown three-dimensional heterogeneities in velocity. We apply these station corrections to each stacked trace by shifting the number of zeros applied before each trace by the station correction value multiplied by the sample rate. For instance, a station correction of -0.10 seconds would mean padding the beginning of the trace with 10 fewer samples before the tf-PWS for that station and 10 more after the trace. We then decimated the stacked traces by a factor of two for 4096 samples at 50 samples per second and passed these traces to the frequency domain using a fast-Fourier transform.

3.4.4 Unconstrained Full Waveform Inversion Method

The inversion methodology we utilized in this study has been employed many times to investigate volcanic LP and VLP events (Chouet et al., 2010; Dawson et al., 2011; Lanza, 2016; Lyons & Waite, 2011; Matoza et al., 2015; Richardson & Waite, 2013; Waite et al., 2008; Waite & Lanza, 2016). Our goal is to determine both a source location and a source mechanism for the event we are evaluating. We calculate Green's functions using Ohminato and Chouet's (1997) finite difference method. Our model space follows the same topography (8.96 km north-south, 11.72 km east-west, and 6 km vertically, centered on the summit of Fuego volcano), dimensions (225x294x151 nodes in the x, y, and z directions respectively), and grid spacing (40 m) utilized by Lyons and Waite (2011) and Waite and Lanza (2016). We use the velocity modeling results from Brill et al. (2018) for a compressional wave velocity of 2230 m/s. The shallow locations of the events reported in Brill et al. (2018), the wavelengths (2 Hz maximum frequency) of the observed events, the effects introduced by errors in a velocity model (see Waite et al. (2008), Trovato et al. (2016), and Discussion below), and the application of station corrections to each trace justify a homogenous velocity structure, although this is acknowledged as a source of error. We calculated an estimated shear wave velocity of 1345 m/s by assuming a Poisson solid, and a density of 2000 kg/m³ using relationships published by Brocher (2005). We

improve stability in the inversion by convolving Green's functions with a half cycle cosine wavelet.

For the source locations, as in the studies listed above, we assume a point source embedded in an elastically responding homogeneous medium which accounts for topography. We also use the reciprocal property (Aki & Richards, 2002) to perform a grid search over a tetragonal volume within the upper cone for possible source locations, treating each station in our network as a virtual source and each node within the volume as a virtual receiver. As the source mechanism is unknown in each of these cases, we perform an unconstrained inversion evaluating source mechanisms represented by the six unique moment tensors, ignoring single forces after suggestions by Trovato et al. (2016) and Lanza (2016). A best location for each event must minimize the error between modeled synthetics and the phase-weighted stacks of each event, produce a source time function which is stable in time, and be geologically reasonable.

We measure squared error after (Chouet et al., 2003; Ohminato et al., 1998):

$$E_1 = \frac{\sum_{n=1}^{N_\tau} \sum_{p=1}^{N_s} (u_n^0(p\Delta t) - u_n^s(p\Delta t))^2}{\sum_{n=1}^{N_\tau} \sum_{p=1}^{N_s} (u_n^0(p\Delta t))^2}$$

where N_τ is the number of seismic traces with N_s samples in each trace, N_r is the number of three component receivers, $u_n^0(p\Delta t)$ is the p th sample of the n th data trace, $u_n^s(p\Delta t)$ is the p th sample of the n th synthetic trace. We consider E_1 the best measure of error for our scenario because it allows equal weighting of each input channel and does not penalize NW1 for having a missing data channel.

The stability of each source time function over time is measured using the statistic suggested by Matoza et al. (2015) and called g by Waite and Lanza (2016) where:

$$g = \left[\sigma^2 \left(\frac{\alpha_1}{\alpha_3} \right) + \sigma^2 \left(\frac{\alpha_2}{\alpha_3} \right) \right]^{\frac{1}{2}}$$

and α_1 , α_2 , and α_3 are the minimum, intermediate, and maximum moment tensor eigenvalues with σ as the standard deviation taken over the history of the source time function. For clarity, we focus on sections of each moment tensor component where the amplitudes are within 60% of maximum for each source time function and compute both the ratios of the intermediate eigenvalue and the minimum eigenvalue to the maximum eigenvalue. We then calculate the standard deviations of these ratios and report g as the norm of these standard deviations. The 60% threshold ensures that only the major features of noisy source time functions are included in the metric.

Finally, our geologically reasonable criteria mean that possible sources are limited to a relatively small area in the shallow cone. We justify this decision based on the lack of any drastic reorganization of the vent system in the subsequent 6 years of eruptive activity since our data was collected, despite several periods of increased eruptive activity (Naismith et al., 2019). Personal communications with INSIVUMEH staff and visual comparisons of satellite imagery indicate that any observable changes to the volcanic edifice are restricted to the immediate vicinity of the active vents or to the barranca systems which trend south. The horizontal position of the vent has remained within roughly 200 m from the long-term position of the main vent. We constrain the depth of possible sources to 1 km below the top of the model due to each event family's waveform and particle motion characteristics (See Section 3.6.3 in Discussion).

3.4.5 Nonlinear Inversion for Moment Tensor Source Type and Orientation Method

The full waveform inversion yields a source location and a quantified uncertainty for that location. We can also infer some of the physical components of the source – the type of mechanism and its orientation – by comparing the point-by-point eigenvector decomposition of the individual moment components, which allow us to interpret mechanism type and orientation (i.e. Chouet et al. (2003)). We further this approach to quantify the uncertainty related to our interpretations of those physical components using the method of Waite and Lanza (2016), which compares data to time constant moment tensors at a given source location within the model, and then uses a grid search over five parameters (γ , δ , three angles of rotation) to explore the complete assembly of possible moment tensor types and orientations for that location. We use the fundamental lune parameterization of moment tensors as described by Tape and Tape (2012). These authors show that all possible moment-tensor source types can be mapped onto a surface and referenced with spherical coordinates γ and δ , which are defined by the ratios of the moment-tensor eigenvalues. Using the surface spline method described in the same study assure computationally efficient and even sampling of the source-type space.

We evaluate the longitude parameter γ from -30° to 30° . As the latitude parameter δ represents the opposite sign of volume contribution from the upper half of the lune to the lower half of the lune, we evaluate δ from only 0° to 90° , instead of the full -90° to 90° after Waite and Lanza (2016). This leaves us with 223 γ - δ pairs. The orientation for each of these possible γ - δ pairs is then sampled at 15° intervals, which testing revealed were small enough to show the general pattern of misfit on the lune diagram with only minor variations in misfit values (Lanza & Waite, 2018a). This results in combinations of rotation angles, which when combined with the 223 pairs, yields 39,744 trial moment-tensor solutions per location under consideration. Misfit between these trial moment tensor solutions and the recorded data is then again calculated using Equation 1.

3.5 Inversion Results

As discussed earlier, the moment-tensor solution depends on the event location and in some cases, it is preferable to use first motion picks to identify the hypocenters before solving for the source. In the case of many LP events, and certainly for VLP events, this is difficult due to the emergent nature of the waveforms. The large uncertainty body wave timing translates into large hypocenter uncertainties. The event locations from velocity modeling work reported in (Brill et al., 2018) suffered from this problem for many events. The LP events located to the north of the vent, but had large uncertainties of 100s of m. The lack of activity to the north of the vent any time between the earliest aerial photographs in the 1940s and the six years since the data was collected, as well as the poor location constraints, suggest these event locations are unreasonable. Instead of using these event locations as starting points for an unconstrained inversion, we use results suggested by g values to determine the most likely location and report error values for these nodes as well as the global minimum error values. We investigate how those solutions compare with nodes in the model which represent spaces nearest to the summit vent and 300 m below the summit vent as these locations also represent likely sources of real activity.

We attempted many variations of the inversions for each of the two event families identified by REDPy. We varied the number of channels included in the inversion, the length of error windows evaluated, and even the length of the signal which we included within the inversion. Comparing events within each stack, as well as looking at regional earthquakes recorded on the network at each individual stations and channels, we ultimately concluded that the S station was showing site effects which we were not adequately modeling with our Green's functions. Similarly, the east component of the NW1 station showed markedly higher amplitudes than the other horizontal channel of the same seismometer or when compared to signals arriving at other stations within the network, which leads us to conclude that regardless of the cause, it is not a reliable channel to include in the inversions, ultimately leaving us with 23 channels for the inversion.

Previous studies have identified challenges with and limitations to performing moment tensor inversion in the LP band (Dawson et al., 2011; Lanza, 2016; Lanza & Waite, 2018a; Trovato et al., 2016). While we acknowledge that the challenges of working in this frequency band mean that we may not be able to definitively constrain the source process, we seek to push this approach through a careful examination of the model space, as well as through other information (i.e. six years of intervening time and relative stability of the vent arrangement in that time and pulse-like nature of events pointing to shallow locations) to achieve a qualitative understanding of the events. In an open vent setting, the workflow of identifying repeating events and passing them through unconstrained full waveform moment-tensor inversion can still produce interpretable results with important information about any possible changes in the activity.

Furthering this approach, despite possible actual single forces included in a source mechanism involving fluid transport through the volcanic system, we use recommendations from previous studies concerning the spurious effects introduced by the inclusion of single forces (Bean et al., 2008; Louis De Barros et al., 2013; Lanza, 2016; Trovato et al., 2016), and only consider the six unique moment tensors in this work. We also rely on a homogenous velocity model due to the fact that Trovato et al. (2016) showed that for shallow LP events, even adding complicated velocity structures to a model will not improve results for shallow events, as the true velocity structure of the shallow subsurface in volcanic environments is likely too complicated to account for in most cases. Including station corrections as discussed above is our attempt to incorporate as much information as possible about the velocity structure of the volcano without introducing extra sources of error in the inversion.

Despite the many variations we attempted, we were unable to generate consistent outputs with errors low enough in geologically reasonable locations for us to confidently interpret the model results from the stack of the first repeating LP event family. However, repeating LP Event Family 2 returned results which were stable enough across the different configurations to interpret. This is perhaps because of the higher signal-to-noise ratio of the individual events included in the stack, but more likely due to the lower frequency content of Event Family 2 (Figure 3-1). When comparing the two event family phase weighted stacks, the peak frequency of Event Family 1 is 1.8 Hz compared to 1.2 Hz for Event Family 2. Even more striking is the distribution of the overall spectral energy in each stack. In Event Family 1, 61% of the total spectral amplitude is below 2 Hz, whereas Event Family 2 has 95% of the total spectral amplitude less than 2 Hz. The velocity model lacks any detail about small-scale structure in the edifice, so we have a more difficult time modeling higher frequencies. For example, if we assume a P-wave velocity of 2.23 km/s as in Brill et al. (2018), the peak frequencies of Event Family 1 and 2 correspond to wavelengths of 1.2 km and 1.9 km, respectively. At the recording distances of 0.8 to 2.1 km our simple velocity model evidently provides enough information about the longer-wavelength signals but lacks detail necessary to adequately model the higher frequencies of those events in Event Family 1.

We report the E_1 misfit and g values for four locations from the unconstrained inversion of Event Family 2 in Table 3-1: 1) the location with the lowest E_1 ; 2) the location with the

Table 3-1. Best solution of unconstrained moment tensor inversion results from the 23-channel configuration.

		Location from Summit (m E-W, m N-S, m, below)			E_1	g	Eigenvalue ratios
RLP Event Family 2	min E_1	0 m E	480 m S	400 m below	0.3243	0.2784	1,0.13,0.30
	min g	240 m E	40 m N	240 m below	0.3789	0.0097	1,0.25,0.13
	Summit	0 m E	0 m N	80 m below	0.4106	0.1098	1,0.18,0.09
	Summit-320m	0 m E	0 m N	320 m below	0.3437	0.1093	1,0.29,0.11

Figure 3-2. Synthetic source volume with best fit locations for repeating LP Event Family 2. The blue square denotes the node with the lowest misfit between real and synthetic data, surrounded by a blue volume showing the extent of solutions with errors within 25% of this minimum (extends to top of possible nodes, which is two nodes below topography). The red square shows the location within that error volume of the node with the lowest value for g , with the red volumes denoting other nodes that have two times the minimum g value or less. Hollow squares and shadows show projections of the solid squares and volumes onto related planes. Contours are at 100 m intervals with the highest contour at 3800 m above sea level and the lowest contour representing 2800 m above sea level.

lowest g ; 3) a position 80 m below the vent (the closest position allowable with the finite difference code, which needs all sources to be two nodes below the surface); and 4) a position 300 m below the vent. All results were computed using the 23-channel configuration and source locations are given with respect to the summit.

The most stable source time function as measured by g for the phase-weighted stack of Event Family 2 is located 240 m east, 40 m north, and 240 m below the summit. Locations which have a g value within two times the lowest g value define an irregularly shaped error volume 5 nodes north and south (± 100 m), 3 nodes east and west (± 60 m), and 5 nodes vertically (± 100 m) from the minimum; we use this volume to define our spatial uncertainty (Figure 3-2). All 15 node locations in this volume have E_1 values that

Figure 3-3. Eigenvalue analysis, source time functions, and modeled versus recorded signal at each station for solution at the minimum g node. **a)** shows rose diagram histograms of point-by-point eigenvalue decompositions with major, intermediate, and minor vectors being represented by red, blue, and green respectively, along with a point-by-point projection of γ - δ pairs at each point where the amplitude was within 60% of the maximum plotted in red circles. The green arc shows crack + double couple tensors with Poisson ratio of $\nu=0.25$, while the black arcs show regions above and below which traditional beachball plots would show only solid colors. **b)** shows the modeled source time functions for each moment component and **c)** is a plot of recorded data (black) vs. modeled synthetics (red) from the synthetic source placed at the minimum g node for event family 2. The black dotted line indicates that the channel was not used in the error calculations. Error for the residuals was calculated over the entire 15 second range as denoted by the red scale bar.

E1 Values for Constrained Inversion at Minimum g Node

Figure 3-4. Results for constrained inversion. Colors represent Error (E_1) for the lowest misfit tensor orientation at each γ - δ location. The dark region suggests that the source mechanism is best represented as a crack with some volume change by showing best misfit nearest the green arc representing crack + double couple tensors with Poisson ratio of $\nu=0.25$ and above the black arc representing the region above which a beachball plot would plot as solid compressional motion.

are within 25% of the global E_1 minimum and modeled source-time functions with dominant moment tensor components that correlate at 75% or better. The synthetic traces match the real phase-weighted stacks reasonably well, with the largest mismatches found in the coda of the stations farther from the vent, such as NW2 and the two SW stations (Figure 3-3c). This coda energy most likely results from unmodeled features of the volcanic structure that are missing from the Green's functions, not unmodeled features of the seismic source. Point-by-point eigenvalue decomposition of the minimum g location yields mean eigenvalues [1.00, 0.25, 0.13] scaled by 8×10^{10} Nm (Figure 3-3b). The mean azimuth (ϕ) and plunge (θ) of the maximum eigenvector is approximately 359° and approximately 44° respectively. Using the fundamental lune source type parameterization of Tape and Tape (2012), we also map these eigenvalue decompositions into γ and δ space yielding averages of 23° for γ and 50° for δ (Figure 3-3a).

At this minimum g node, we then constrained the source mechanism to remain stable in time and then rotated that mechanisms orientation as discussed above. Figure 3-4 plots

Figure 3-5. Full stack of 368 events (NE1 vertical channel) identified in REDPy with a minimum correlation coefficient of 65% on three channels or more. Events highlighted in yellow were also grouped with event family 1 and a green highlight denotes membership in event family 2.

the E_1 for the lowest misfit tensor orientation at each moment tensor type. The lowest values are in the region immediately surrounding the arc which represents crack + double couple tensors with Poisson ratio of $\nu=0.25$, with a region of the best 0.5% values plotting above the line where a beachball plot would show only as solid colored, isotropic moment tensors.

3.6 Discussion

We have identified two families of LP events and modeled the location and source mechanism for one of those families in the upper edifice of the volcano. Here we discuss details of the similarities between the two families and other events as well as some interpretations for LP source process at Fuego.

3.6.1 Event statistics and similarities

One way to better understand the driving processes behind these events is to examine statistics of the repose times between events. Varley et al. (2006) investigated the coefficient of variation for the interevent times to determine if events are occurring independently of other events in a given set or in some way dependent upon what happens prior to each event. A coefficient of variation of 1 or lower implies a governing Poissonian process of renewal, and above 1 suggests that the process of renewal is clustered and possibly driven by the interaction of more than one factor. Table 3-2 shows the coefficients of variation for the interevent times of both families of events and their constituent numbers of events. The coefficient of variation statistics suggests clustered governing processes for both event types. The number of events used for timing differs slightly from the number of events which were used in the phase-weighted stacks because we required that all network channels were running for an event to be added to the stack, but this restriction was lifted to increase the catalog size of each family of events.

One interesting thing about the two phase-weighted stacks is that they have a maximum cross correlation value of approximately 57% on the NE1 channel. In our REDPy trials, we considered lowering the correlation threshold of events down to 65%, and one of the returned families in that trial contained 368 constituent events which included 119 out of

Table 3-2. Event family timing statistics. Tau bar is mean interevent time, sigma tau is the standard deviation of the interevent time, and cv is the coefficient of variation.

Event Type	Number of Events	$\bar{\tau}$ hh:mm:ss.sss	σ_{τ} hh:mm:ss.sss	c_v
65% Correlation Combined Group	368	00:31:03.638	00:57:02.717	1.8366
Event Family 1	123	01:33:26.188	02:23:48.571	1.5391
Event Family 2	25	07:23:13.918	12:21:53.392	1.6738

the 123 events from Event Family 1 and 23 of the 25 events from Event Family 2. Figure 3-5 shows self-normalized traces recorded on the vertical channel of NE1 with the constituent events from Event Families 1 and 2 highlighted in yellow and green respectively. So, while the event families can be viewed separately, they share similarities indicative of a similar source process.

The similarities in the waveforms between these two event families when looking at the signals captured across the network points to similar driving processes behind these observed events. Both event families are very likely caused by volume changes of cracks of different orientations at different depths around the conduit margins. If we look at the 368 events as a class of Repeating Long Period (RLP) events, the coefficient of variation increases. The expanded set includes some larger amplitude events, along with 15 events which overlap with visibly observed emissions, but as stated above, no visible emissions are associated with any member of Event Family 1 or 2. We observed infrasound signals associated with six events in Event Family 1, one event in Event Family 2, and a total of 26 events in the expanded RLP set. Only 6 total events have both visibly observed emissions and associated infrasound signatures. Some events with visible and/or acoustic emissions may escape detection due to environmental variables (clouds for visibility, wind for infrasound), but larger amplitude events are more likely to be associated with these additional signals (Figure 3-6c).

Brill et al. (2018) report that the degassing events emanating from the volcano appear to follow a Poissonian process, and Nadeau et al. (2011) report interevent degassing occurring at Fuego during other observation periods. If the clustering of these RLP events is due only to different amounts of some magmatic gas being trapped in a system of cracks, there should be a trend in larger events associating with longer repose times. It may be that there are associated gas emissions with each of these events, only their smaller size means they are less likely to carry large quantities of ash and are less likely to be visibly detected overall.

The source of this clustering may be related to the overall energy leaving the system. We use peak-to-peak amplitude of the initial pulse on station NE1 (chosen because of its proximity to the vent as well as its longer operational time when compared to NW1) as an analog for event magnitude. When plotted against the time since the last RLP, there is no obvious correlation between larger event amplitudes and longer interevent times (Figure 3-6a). A look at amplitudes of events versus the cumulative number of events with that amplitude or greater also shows unremarkable event scaling in a volcanic environment for any type of earthquake (Figure 3-6b). When comparing RLP events to peak to peak amplitude measurements from the onsets of visibly observed events, the RLPs are separated by an order of magnitude on average, but there are no other noticeable trends (Figure 3-6c). However, the number of events per hour do show an inverse relationship to hourly averaged measurements of seismic amplitudes (Figure 3-6d). Brill et al. (2018) noted that average absolute seismic amplitude measurements (i.e., RSAM (Endo & Murray, 1991)) from this period on station NE1 was dominated by volcanic tremor with spikes due to regional earthquakes. Nadeau et al. (2011)

Figure 3-6. a) Time since the last repeating LP event in seconds plotted against the amplitude of that event. b) Amplitude of events plotted against the cumulative number of events with that amplitude or greater. c) Time of each event plotted with the amplitude of each event sorted into two event types. Of the 368 RLP events, members of Event Family 1 are circled in red and members of Event Family 2 are circled in blue. Any event with a co-occurring acoustic emission is also highlighted in green. d) Number of events per hour for each day plotted with the hourly average real time seismic amplitude.

Figure 3-7. Comparison of source time functions and their eigenvalue decompositions from different nodes within the model space returned by the unconstrained full waveform moment tensor inversion. In each subplot, red represents information from the 15 best g nodes, green represents information from the nodes 80 meters and 320 meters below the vent in the model, and blue represents information from the minimum E_1 node. a) shows the lune projections of the γ - δ pairs at each point where the amplitude was within 60% of the maximum. b) is a plot of all the M_{zz} components of the source time function for each of these nodes. Each component is labeled with the E_1 and g values on the right and the node model coordinates and correlation coefficient with respect to the M_{zz} component of the best g node on the left. c) shows the rose diagram histograms of the different orientation information obtained from the point-by-point eigenvalue decompositions showing azimuth (ϕ) and plunge (θ).

found a correlation between nonharmonic tremor and gas emission measured with a UV camera in 2009 and that type of mechanism was likely to be active in 2012 as well. While tremor could make detection of the smaller RLP events more difficult, it is also likely that these small RLP events occur as a response to degassing by a mechanism similar to the tremor, but during periods of low flux when gas pressure cannot sustain tremor.

3.6.2 Eigenvalue decompositions

We consider the event locations reasonable but chose to explore the similarity of best-fit solutions throughout the model space to examine the effect of location on modeled moment tensor. In particular, we compare source-time functions from all the nodes which were both in the best 25% of the synthetic source volume for E_1 , as well as being within twice the minimum value of g . Figure 3-7a plots the eigenvalue decompositions of Event Family 2 on the fundamental lune for these 15 nodes within the red volume of Figure 3-2 in red, along with the node with the minimum E_1 node in blue and nodes located 80 meters below the vent and 320 meters below the vent are both in green. Each of the best g nodes produce source-time functions that plot between cracks with Poisson's ratio of 0.25 and dipole mechanisms. The solutions for nodes 80 meters and 320 meters below Fuego's vent (green circles) and the minimum E_1 node (blue circles) plot close to this line as well, but the source-time functions from these three other nodes are markedly different from the model results from the best g nodes. This can be seen in both the correlation values of the M_{zz} component of the source-time functions at those nodes (Figure 3-7b), as well as the rose diagram histograms for their eigenvalue decomposition orientations (Figure 3-7c).

One other point, the clustering of these eigenvalue decompositions from the different best g nodes and the similar location of the region of minimum E_1 misfit shown in the constrained inversion results in Figure 3-4 correspond to a region on the fundamental lune which corresponds with Poisson ratios slightly lower than 0.25 (Tape & Tape, 2013). This value may be expected for Fuego based on comparisons to very hot basalts at Mt. Etna, Italy by Heap et al. (2009), as well as from basalts from the Galapagos, Ecuador and the Columbia River Basalts in Oregon, USA by Murase and McBirney (1973). The differing values for ϕ and θ can be attributed to differing orientations of the different cracks which open and close releasing different volumes of magmatic gasses. Instances of similar mechanisms have been observed at different volcanoes driven by rapid phase changes of magmatic gases (Arciniega-Ceballos et al., 2012; Caplan-Auerbach & Petersen, 2005; Chouet & Dawson, 2016; Maeda et al., 2013; Matoza et al., 2015; Waite et al., 2008), sometimes but not necessarily involving interaction with a hydrothermal system or water table.

3.6.3 Cracks vs. Brittle Failure

Bean et al. (2014) posit that ringing codas observed in many LP events are due strictly to path effects and that short pulse-like signatures observed in Italy's Mt. Etna in 2004 and

2008, as well as Costa Rica's Turrialba Volcano and Peru's Ubinas Volcano in 2009 are caused by slow-rupture earthquakes related to volcano-tectonic earthquakes but in the more ductile medium near the surface in volcanic environments. Chouet and Dawson (2016) use cross correlations between those measured waves and those from numerical simulations of ground responses of both a fluid-driven crack and a slow-rupture tensile dislocation to show that a better fit is achieved between modeled and observed data with a fluid-driven crack source.

Unfortunately, the Fuego data set is not high enough quality to support testing whether events show corner frequency scaling with amplitude. We can report that we did not observe any relationship between event amplitude and peak frequency, which might serve as evidence against slow rupture earthquakes. Furthermore, Brill et al. (2018) found the peak pulse in the phase-weighted stacks of some events exhibited retrograde motion characteristic of Rayleigh waves. This characteristic was also noted by Chouet and Dawson (2016) in the Etna data and they found they could only reproduce this in their synthetics with a very shallow source. Event Family 1 has a strong pulse like Rayleigh wave around the network (Chouet & Dawson, 2016). Event Family 2 showed a similar order of relative arrival times and did not show any good fit deep locations during any of our initial tests, which included multiple different channel geometry configurations and different tapering windows to try to focus on just initial pulses of the waveforms.

3.6.4 Longer-term observations of the LP source

The 2012 deployment was just a couple of weeks long, so an obvious question related to the significance of the LP source over longer time spans. We reexamined data collected in similar field campaigns in January 2008 and 2009. While neither campaign had identical station deployments, each of them had a station within about 20 m of station NW1 in 2012, About 800 m north of Fuego's active vent. We chose the location for to be as close as possible to station FS4 from 2008 and F900 from 2009 campaigns (Lyons, 2011; Lyons & Waite, 2011; Nadeau et al., 2011; Waite et al., 2013) and use data from these three stations to compare waveforms across the different campaigns. . Following the 2012 experiment, we returned to the NW1 site with a Güralp CMG-ESPC (60 s – 50 Hz flat response) seismometer and recorded data on a RefTek 130 Data Acquisition System at 50 samples per second. We recorded approximately 1.75 days of data in February of 2014 and approximately 35.7 days of data in January and February of 2015.

We used a time domain match filter (Hopp & Waite, 2016; Lanza & Waite, 2018b; Richardson & Waite, 2013; Shearer, 1994; Shelly et al., 2007) with the phase-weighted stacks from each event family described here as template events. Using a correlation coefficient cutoff of 75%, we detected 56 events from Event Family 1 and 11 events from Event Family 2 in 2008 on the FS4 station, and in the 2009 data from station F900 we detected 10 events from Event Family 1 and 1 event from Event Family 2. In 2014, we detected 8 events from Event Family 1 and 38 events from Event Family 2, and in 2015 we detected 58 events from Event Family 1 and 22 events from Event Family 2. The distribution of amplitudes from the two prior years falls within similar ranges as the

Amplitude Distributions of Repeating Long Period Event Families

Figure 3-8. Event amplitude distributions for each constituent member of the repeating long period event families, sorted by year with number of events on each y-axis and amplitudes in m/sec on each x-axis. Individual events in 2012 were detected by REDPy, and those events from 2015, 2014, 2009 and 2008 were detected using a time domain match filter using the phase-weighted stacks of the 2012 event families as a template. Heading of each subplot notes average event number per hour for duration of operation time in each given year, with red denoting events in Event Family 1 and blue denoting events in Event Family 2.

events we observed in 2012 (Figure 3-8). There were not enough events to form significant sample sizes which would allow for statistical comparison between the events from all the years considered, but the stability of each family over several years strongly points to these RLP events being emitted from either non-destructive sources, or a configuration within the volcanic edifice which is reproduced very often.

This long-term stability of the LP waveforms also favors the interpretation that the events are occurring around the conduit rather than within the conduit itself. Nine LP event families containing more than 45 events each at Soufrière Hills Volcano, Montserrat related well to the time derivative of the tilt, and the initiation order of different families remained constant across different swarms and periods of quiescence (Green & Neuberg, 2006). Multiplet families observed at Mt. St. Helens during 2004 evolved rapidly and associated with different stages of lava extrusion, sometimes occurring with other multiplets in multiplet clusters (Thelen et al., 2008). Event families with higher frequency content at Redoubt volcano in 2009 also changed during different stages of the eruption (Ketner & Power, 2013). These volcanoes all erupt higher silica content magmas, all display waveforms with longer codas, and none persist outside of discrete eruptive phases. Shishaldin Volcano, a basaltic to basaltic andesite volcano, which displayed LP families which persisted on the order of days to months and evolved gradually over a period of several years from 1999-2004, but not a single event persisting over a four-year period (Petersen et al., 2006). The events at Shishaldin show coupling with infrasound signals and are also described as shallow events related to the degassing process (Caplan-Auerbach & Petersen, 2005).

3.7 Conclusions

Based on exhaustive analysis of solutions from nodes throughout the edifice, similar interevent timing statistics, particle motion analysis, and stability over time of the system, we interpret both repeating LP event families which we observed at Fuego volcano in January of 2012 to be generated by rapid pressure changes as magmatic gasses pass through systems of cracks in the shallow subsurface in or surrounding the active volcanic conduit. Additional information from the repeating families of events, specifically event spacing and amplitudes, particle motions, and visual observations help provide constraints on results and increase our confidence in this interpretation and do not support other possibilities such as slow rupture tensile dislocations. The suggested limitations to full waveform moment-tensor inversion in the LP band when it comes to determining exact locations and quantifying volumes mean that we are not able to confidently quantify the amounts of gas escaping through this method, but the uncertainty in location does not exceed reasonable estimates for the location of the conduit and bolsters our interpretations that these are conduit related processes. Observing changes in the rates of these events might give additional information on flux of total material exiting the system not provided through explosion counts or real-time seismic amplitude measurements, especially given the long-lived nature of these signals. This could have direct hazard mitigation application and should be investigated further.

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4 Continued variability of very long period seismicity at Fuego volcano, Guatemala as of January 2012

4.1 Abstract

Fuego volcano in Guatemala manifests very long period (60-10s) seismicity in many different varieties. Waite et al. (2013) described three unique types of this signal occurring in 2008 and 2009. We continue to observe these three types of very long period (VLP) events in 2012, however we observed blurred boundaries between the unique groupings and with lower levels of intensity overall. We add two sub-groupings to the previous classification scheme to include signals previously only observed in concert with emissions from one of the two active vents at Fuego in prior years concurrent with the opposite vent in 2012. We suggest that these events may be part of a continuum of VLP activity which may still share a source with the one modeled by Lyons and Waite (2011), but with magnitudes governed by small changes in the magma supply rates and possibly even atmospheric conditions.

4.2 Introduction

In volcanic environments, very long period (VLP) seismicity is associated with material transport and volume changes of fluids. These signals have been observed in many different volcanic systems around the world, and the exact source mechanisms differ based on the viscosity / chemical composition of a given system's magma. The low frequency content (0.01 to 0.5 Hz) and thereby long wavelengths (tens to hundreds of kilometers) of these signals means less distortion of those signals from the complicated structures at the 10-100-meter scale (e.g. lava flows, tephra layers, translated fault blocks) found around volcanoes. This effective simplification of velocity structures allows for higher confidence in the results from techniques used to investigate the source processes generating this class of signals (Chouet & Matoza, 2013).

At Fuego volcano in Guatemala, several different types of VLP events are described in depth in studies by Lyons and Waite (2011) and Waite et al. (2013) from data gathered during field work conducted in 2008 and 2009. Visible activity issued from two distinct vent areas during these time periods, referred to as the summit and flank vents for their positions relative to each other (Figure 4-1). Waite and others (2013) describe 3 types of VLP events. Type 1 events had emergent onset seismograms and were concurrent with ash rich plumes from the flank vent in 2008. Type 2 events issued from the summit vent in 2009, showed impulsive onset seismograms and featured ash rich plumes. Type 3 were only observed in 2008 and occurred as ash free gas puffs issued from the summit vent and had emergent onset seismograms. These events were also clearly visible in the sulfur dioxide data. In their 2011 paper, Lyons and Waite used full waveform moment tensor inversion to solve for the source of the summit impulsive events (Type 2 events) and

Years each site was occupied

	2008	2009	2012
NW1	x	x	x
NW2		x	x
NE1			x
NE2		x	x
SW1		x	x
SW2			x
SE1			x
SE2			x
N*	x	x	x

*Collocated video, FLIR, and UV camera

Figure 4-1. Contour map of Fuego volcano with locations of temporary seismic stations for 2008, 2009, and 2012.

found the best fit to be a volumetric source about 300 m below and 300 m west of the summit. The best source matched an inflating sill dipping 30 degrees to the west being fed from a near vertical dike.

In 2012, we installed another temporary seismic network at Fuego volcano to further investigate the VLP events, specifically by increasing radial coverage in the south and southeast regions of the active vent, an area of the wavefield which had not been sampled in the 2008 or 2009 field campaigns. The instruments were deployed from January 13th to the 23rd, and all told, the network ran for about 7 days with full station coverage, which included nine broadband seismic stations, two of which included 3 channel arrays of pressure sensors for recording infrasound, as well as time-lapse imagery captured from two separate locations. Figure 1 shows the station locations from the 2008, 2009, and 2012 deployments. For further information about the specific stations see Lyons and Waite (2011), Waite et al. (2013), or Brill et al. (2018).

4.3 VLP Events

This chapter will outline the VLP events associated with vent emissions observed during January of 2012 and compare the events to those observed in 2008 and 2009. Despite recording VLP with each of the event types described in Waite et al. (2013), none of the VLP energy was captured on any of the stations to the south of Fuego's vent during the period of observation. We will therefore be unable to report any new information regarding the actual source mechanisms of the VLP signals we observed, but through careful analysis we will be able to discuss the stability of the source reported in Lyons

and Waite (2011) and Waite et al. (2013) as well as introduce new VLP signals not observed in 2008 or 2009. All data presented as VLP has been filtered using a 4 Pole Butterworth filter between 60 and 12 seconds with instrument responses removed using a water level deconvolution.

To begin our analysis, we reviewed visual records of the activity from January 2012 captured using five separate camera devices. The first two devices were time-lapse cameras referred to as Cam1 and Cam2 described in Brill et al. (2018), and the third device was a Sony Handycam camcorder which recorded images (1440 x 1080 pixels) at 29.97 Hz. This third camera was operated while observers were physically present on the Meseta section of the Fuego edifice and only on the dates of 15 and 17-20 January for a few hours in the morning, and never outside the operational times of Cam1 and Cam2, and as such served as a check when activity captured by one of the other cameras was obscured by clouds or as a window into higher temporal resolution on individual events. Operated at similar times, a Forward-Looking Infrared Radiometer (FLIR) camera and the same UV camera that was described by Waite et al. (2013) for SO₂ emissions. Operations challenges and a lack of calibration consistency meant that we were not able to utilize these instruments to their fullest capacities (i.e. accurate SO₂ flux measurements or exact plume temperatures), but we are able to look for absorption and compare plume characteristics qualitatively to the associated visual records.

VLP events were identified in the 2012 dataset by first looking for visual emissions in the time-lapse camera images and comparing that to raw and filtered seismograms and

Figure 4-2. Detail of Fuego vent region showing approximate locations of the two vents, S for summit and F for flank.

Table 4-1: Summary of Characteristics of VLP Events. Expanded from Waite et al. (2013). January 2012 values are for events on NW1 vertical component

	Type 1		Type 1a
Time Observed	January 2008	January 2012	January 2012
Vent	Flank	Flank	Flank
Peak VLP period (s)	48	49	31
VLP peak-to-peak amplitude ($\mu\text{m/s}$)	0.5	0.33	0.57
Infrasound pressures (Pa)	1-10	0.2-3.5	0.6-45
Style of Emission	Emergent, ash rich	Emergent, ash rich	Impulsive, ash rich

	Type 2		Type 2a
Time Observed	January 2009	January 2012	January 2012
Vent	Summit	Summit	Summit
Peak VLP period (s)	35	40	43
VLP peak-to-peak amplitude ($\mu\text{m/s}$)	5	0.5	0.15
Infrasound pressures (Pa)	100-1000	0.2-286	<0.5
Style of Emission	Impulsive, ash and bomb rich	Impulsive, ash and bomb rich	Emergent, ash poor

	Type 3	
Time Observed	January 2008	January 2012
Vent	Summit	Summit
Peak VLP period (s)	29	30
VLP peak-to-peak amplitude ($\mu\text{m/s}$)	0.5	0.5
Infrasound pressures (Pa)	Not Observed	Not Observed
Style of Emission	Ash-free gas puffing	Ash-free gas emissions

infrasound records from the same time periods. We noted the vent of origin (Figure 4-2) and duration for each emission (which sometimes was truncated by the subsequent emission from the same or neighboring vent), picked broadband signal arrival times, VLP and infrasound maxima and minima for each signal when signal was present. We use these observations to compare activity in 2012 to prior years, as shown in.

We also take advantage of the Correlation Toolbox component of the GISMO seismic data analysis toolbox for MATLAB (Thompson & Reyes, 2017) to explore the variability of these VLP waveforms. Specifically, we can use cross-correlation values to compare each event to every other event in a group and establish clusters of events, hierarchical relationships between different events, and linkages between clusters.

We performed a moving window time domain match filter using several different templates. Our goals were to improve signal to noise ratios on the southern stations and test the reliability of being able to distinguish which vent was active by VLP characteristics alone. Despite creating both linear stacks and phase weighted stacks, no coherent signal was present to the south, and very little signal is discernable due to low signal to noise ratio even on the NW2 and NE2 stations. Even on the several largest individual events and stacking those events, we were not able to generate enough signal on the southern network stations to perform further analysis. Although disappointing from a modeling perspective, this is enough to point out a major difference between activity levels in January of 2009 and January of 2012: though the variety of events is greater than observed in 2009 or 2008, the instances of each type of activity was less intense in each case.

4.3.1 Type 1: Flank Vent, Ash Rich, Emergent

The Type 1 event class identified by Waite and others (2013) was only observed in January of 2008. The events were long duration (20-150 seconds) ash-rich explosions from the Flank vent with low infrasound pressures. Peak excess pressures were at a maximum 10 Pa, which was only about 1% of the largest excess pressures from the 2009 explosions, and in most cases had nearly undetectable infrasound signals. Scientists observing the volcano in 2008 while data was being collected reported not hearing sound associated with the events. Peak periods for these events was 44 seconds, which was the lowest for the three VLP types reported by Waite et al. (2013). The Type 1 events were the only events previously observed originating from the flank vent in either 2008 or 2009.

In 2012, we observed a total of 72 events originating from the Flank vent region. Associated eruptive material consisted of plumes ranging from fast rising, optically dense, and ash-laden to slow moving, translucent, and ash-poor during the daytime, and at night some events included many large, incandescent, ballistic material which was visible as it exited the vent and traveled down the flanks of the volcano. Thirty-four of these events included infrasound signals which were detectable above background activity on one or more of the deployed pressure sensors, and five of these events had peak excess pressures above 10 Pa.

A correlation coefficient of 80% splits the 72 flank events into two separate clusters of 12 and 55 separate events with 5 events not correlating to either group above 30%. The group of 12 events contains only 2 events with infrasound signals, the largest of which registers just below 4 Pa excess pressure. These 12 signals have an average peak period of 49 seconds and visible emission durations from 10 to 115 seconds with a mean of 65

Type 1

Figure 4-3. Type 1 VLP events from January 2012. a) and b) show vertical traces from NE1 and NW1 respectively, with individual events plotted as fine lines and the thicker line as the linear stack of events. The spectra from each stacked trace is plotted directly below in c) and d). Green lines in each plot represent stacks of events filtered from 120-12 seconds for reference.

seconds (Figure 4-3). The similarities in waveform shape, spectral content, and similar infrasound characteristics to the Type 1 events observed in 2008 let us feel confident that these signals are from the same or very similar source in 2012.

Type 1a

Figure 4-4. Type 1a events from January 2012. a) and b) show vertical traces from NE1 and NW1 respectively, with individual events plotted as fine lines and the thicker line as the linear stack of events. The spectra from each stacked trace is plotted directly below in c) and d). Green lines in each plot represent stacks of events filtered from 120-12 seconds for reference.

4.3.2 Type 1a: Flank Vent, Ash Rich, Impulsive

The second group of events originating from the flank vent have a visibly different shape (Figure 4-4). Of these 55 events, 32 have associated infrasound signals with peak excess pressures ranging from undetectable to 45 Pa. The 55 events in this group have a higher average peak period of 31 seconds and visible emission durations from 5 to 128 seconds

Type 2

Figure 4-5. Type 2 VLP events from January 2012. a) and b) show vertical traces from NE1 and NW1 respectively, with individual events plotted as fine lines and the thicker line as the linear stack of events. The spectra from each stacked trace is plotted directly below in c) and d). Green lines in each plot represent stacks of events filtered from 120-12 seconds for reference.

with a mean of 63 seconds. The associated emissions for this type of event are almost always faster rising than the Type 1 Flank events, with explosions which sometimes carry ballistics and heavily ash laden plumes during the day and much more incandescent material visible associated with the nighttime explosions of this group. The behavior of these flank events is much closer to the smaller summit explosions observed during 2009, and therefore blurs the lines between our ability to distinguish vent activity using purely seismic signals.

Figure 4-6. Comparing maximum velocity amplitudes from 2009 (purple *'s) and 2012 (green x's).

Type 2: Summit Vent, Ash Rich, Impulsive

Type 2 events described by Waite and others (2013) were ash-rich explosions from summit vent. Observed in January of 2009 and explored in detail first by Lyons and Waite (2011), the events generally lasted less than 60 seconds, had excess pressures which could measure more than 1 kPa, and a peak VLP period of 35 seconds.

We captured images of 176 events originating from the summit vent region during 2012. These events had visible durations from 5 to 400 seconds on several occasions with a mean duration of 82 seconds. We again used a correlation coefficient threshold of 80% to identify different clusters of events and found one cluster containing 151 events, a second with just 12 events, and 13 events which did not correlate to any other events above a 75% threshold. The larger cluster containing 151 events matched the description given by Waite and others (2013) of the Type 2 class of events from 2009, albeit with somewhat smaller and slightly longer peak periods. Peak VLP periods in 2012 were closer to 40 seconds (Figure 4-5), and infrasound excess pressures only reached a maximum of 286 Pa. These were the most prevalent subgrouping of events observed at Fuego during January 2012.

Lyons and Waite (2011) presented peak amplitude measurements from 52 VLP events on the F900 station with 85% or greater cross-correlation coefficients. We do not have the exact catalog from the 2011 paper but using a threshold of 86.5% on the vertical channel, we are able to retrieve similar trough-to-peak amplitudes when looking at the North channel of F900. In 2012, we took the same measurements of the 151 events Type 2 events we identified and plotted them on the same axis for comparison (Figure 4-6). Lyons and Waite (2011) reported volume changes between 192 and 2062 m³ and using the same linear relationship from amplitude to volume, we can report volume changes only from 0.15 - 10 m³, which corresponds to the much lower maximum velocities.

Type 2a

Figure 4-7. Type 2a VLP events from January 2012. a) and b) show vertical traces from NE1 and NW1 respectively, with individual events plotted as fine lines and the thicker line as the linear stack of events. The spectra from each stacked trace is plotted directly below in c) and d). Green lines in each plot represent stacks of events filtered from 120-12 seconds for reference.

Type 2a: Summit Vent, Ash Poor, Emergent

The second group of events which visibly emanate from the summit vent seem to match the overall VLP waveform shape which we observe as Type 1 events in both 2008 and 2012, with the one caveat that the vent of origin is distinct. There are only 12 events of this type recorded on the 2012 network, and of these only 9 were recorded on the NW1 station due to station down time. Infrasound excess pressures are only detectable with 2

Figure 4-8. Two events captured with multiple instruments. The top row shows a Probable Type 3 VLP event recorded at 2012-01-18 14:51:58 UTC on the FLIR (right) showing infrared and video camera (center) just prior to the start of UV camera recording. The bottom row shows a plume emission detectable only on the UV camera several minutes later at 2012-01-18 15:04:21 UTC after data collection began on the UV camera. Again, from right to left: Infrared, Visible Light, and Ultraviolet. The IR and Visible images show little to no evidence of a plume, but absorption in the UV spectrum is clear. The center row shows two seismic traces, both from the vertical channel of station NE1, but the top trace is filtered from 0.1-25 Hz and the bottom trace is filtered from 60-12 seconds. Red lines indicate timing of pictured events.

of these events, and they are each less than 1 Pa. The plumes for these events are mostly ash-poor translucent emissions, varying in duration from 16-130 seconds. The peak VLP period is close to 44 seconds, another similarity this class shares with Type 1 summit events (Figure 4-7).

Type 3

Figure 4-9. Type 3 VLP events from January 2012. a) and b) show vertical traces from NE1 and NW1 respectively, with individual events plotted as fine lines and the thicker line as the linear stack of events. The spectra from each stacked trace is plotted directly below in c) and d). Green lines in each plot represent stacks of events filtered from 120-12 seconds for reference.

4.3.3 Type 3: Summit Vent, Ash Free

Type 3 events were seen in 2008 only and are different in that they are associated with ash-free puffing from the summit. The lack of a visible plume presented a challenge to us for identifying these events in 2012. After reviewing all VLP activity associated with vent activity while visual images were being recorded, we went back and looked for VLP

signals occurring during times when the cameras were operational, but no emission had been noted. As noted above, the UV camera was operational and recording for approximately 30 minutes during the campaign on the morning of 18 January 2012. No VLP events were recorded during that hour, but there was one which occurred during equipment setup. The video camera was recording prior to the start of recording on the UV camera, and happened to capture a conversation between the two scientists operating the cameras.

Approximately 30 seconds after a VLP event is clearly seen in the seismic record (Figure 4-8), one scientist remarked “there is a lot of degassing, I just took this image it’s like thirty seconds ago.” The second scientist agreed, “It’s really cool you can see that, it looks totally different.” While this calibration image was not saved for further analysis, it stands as evidence for the possibility of Type 3 events in 2012. Images captured several minutes later once data collection had begun on the UV camera clearly show a plume coming from the summit vent which is not visible on the video camera and does not register in the infrared images either.

Assuming this event type did occur during 2012, we identified nine events which registered as small VLP events but were not visible in any of our recorded images. The only way for certain to confirm the presence of a Type 3 event would be to capture it using the UV camera, but unfortunately, the half hour of data which we recorded did not contain any of these VLP signals. Several of the events grouped with the categories already mentioned had very minimal plumes, and wind speeds at the summit were often great enough that dust picked up from the windward flank made distinguishing small plumes difficult. Wind also created difficulties for identifying small events from the vantage point of Cam1, small flank events were sometimes unobserved before the plumes were carried off. Of the 9 events, 6 events correlate above 80%, none of which have any corresponding infrasound signature. The peak VLP period is 30 seconds (Figure 4-9).

4.4 Discussion

Activity in 2012 showed both remarkable consistencies and some important differences to the activity observed in prior years. The single largest change seems to be with the magnitudes of the explosive events. While there are events which would still fall into the Type 2 class from 2009 observable in 2012, the largest events from 2012 are on par with the smallest events observed in 2009. The distinct waveform shape from the 2008 Type 1 Flank events do not have the same distinct vent separation in 2012. Both vents produce emissions with each general type of VLP waveform. Both the trough-peak motion on the vertical channel of the more emergent types of events and the trough-peak-trough signals associated with the impulsive activity can originate from each vent.

There is not a hard line between Impulsive and Emergent events in the VLP signal. The main difference if any, is that ash poor events tended to be lower amplitude, and the large events were always very ash rich in 2012. The main difference between type 2 and type 3 is the lack of infrasound in the type 3 events, but as ash content of the plumes can be

Figure 4-10. Number of events with a given peak period grouped by type.

difficult to discern, it seems likely that these events all represent more of a continuum of activity styles than strictly ordered groupings. The Flank Impulsive events were also difficult to separate seismically, and with winds on some of the days blowing strongly from the east to the west, the visual distinction wasn't always straightforward either. Regardless, the ashy emissions clearly from the lower vent still had a very similar VLP to the summit ashy vents.

The largest obstacle to extracting more information from these VLP signals remains their small amplitudes and therefore low signal to noise ratios. We looked for differentiating characteristics in the spectral contents of the different events, but Figure 4-10 shows the

Figure 4-11. Polar plots of particle motions measured on station NW1. Each event is a self-normalized sum of self-normalized traces.

wide distribution of peak amplitudes associated with the different signal types. However, upon stacking groups of events linearly, the peak frequencies of the explosive events (Type 1a and Type 2) from 2012 are near the same frequencies reported by Waite et al. (2013) for Type 2 events from 2009, and the combined emergent events (Type 1 and Type 2a) also match within 5 seconds (Table 4-1). We also produced polar plots of particle motions from these stacks of events, which also resemble motions from Waite et al. (2013) (Figure 4-11).

Allowing for differences due to the much lower signal to noise ratios of each constituent signal, the similarities of the stacked events to events observed in 2008 and 2009 indicate that the VLP source has been stable since at least 2009, and that the model of Lyons and Waite (2011), at least for the Type 2 event remained valid in 2012. Similarities in waveform shape between events tied to different vents and even with different emission styles point to similar origins even between these different emission styles and indicates that the vent which releases material represents more of a path of least resistance than a governing process for a given VLP.

Lyons and Waite (2011) best fit source was a steeply (65°) dipping dike feeding a shallowly (35°) dipping dike which intersect roughly 300 m below and 300 m west of Fuego's summit. Both Lyons et al. (2012) and Waite and Lanza (2016) explore the effect of tilt on the recordings during 2009. Tilt signals began several minutes prior to explosions and is interpreted as representing pressurization within the conduit, most probably in the sill portion above the feeder dike. Lyons and Waite (2011) discuss the formation of a crystal rich cap which seals or partially seals the otherwise constantly degassing conduit, allowing pressure to build until an explosion occurs. That same degassing allows much of the magmatic water content to escape as the magma nears the surface, speeding crystal growth and allowing the mafic magma to exhibit more silicic behavior.

One addition we can now add to this model is that the seal which is breaking may at times begin below the split in the conduit separating the two vents. In 2012, in addition to seeing waveforms and associated activity show much less strict vent preference there are also several examples of VLPs and emissions happening very closely together, within a span of under two minutes. In one example, a series of events begins with a summit emission, starts a flank emission almost as soon as sky can be seen between the plume and the summit vent, and ends up with another summit emission before the ash can clear from the flank emission. This grouping of events suggests that the pathway for escaping ash and gas may be complex. The cap may vary in thickness from event to event(s) at least in times of less energetic activity.

When examining the deposits of Fuego's 1974 sub-Plinian eruption, two studies discuss different ascent rates for different magmatic constituents at Fuego. Anderson (1984) discusses the sub-micrometer zoning of plagioclase crystals as indicators of possibly tidally driven oscillations of magmatic fluids which move faster or slower around growing crystals depending on gravitational forces. Lloyd et al. (2013) discusses

differences in volatile loss from eruptive products based on the size of the pyroclasts in which they were hosted. Both studies were carried out on older eruptive products, but another study comparing 1974 products to material collected as recently as 2006 indicate that the magma chemistry has not dramatically shifted (Berlo et al., 2012).

The stable vent arrangement for most of the current eruption (since 1999) points to a well-established conduit geometry, which would imply a distinct interface between material within the conduit and conduit walls. The preferential motion of liquid around solids deeper in the conduit system and gas and liquid around and between larger solids and any conduit constrictions at shallower depths may allow for a kind of self-organization into zones with more volatiles and crystals and zones with less. As these different portions of material ascend and near the surface, these slightly different saturations could be enough to account for groupings of VLPs and explosions or tremor in general, as well as even quieter periods in a given day, especially during low activity periods like we observed in 2012. In periods of greater magma flux, these factors and obstacles would have differing degrees of influence on activity depending on their individual scales.

4.5 Conclusion

There does not appear to be a significant difference between the activity at the two vents emitting material in 2012 and their associated VLP signals. The differing activity styles observed at Fuego in 2008 and 2009 are also observed in 2012, but in general with lower intensity levels, and seismic signals before only associated with one vent of emission in prior years are observed at both vents in 2012. We report the variability of these signals with the hope that further investigations can build on this work as we have increased the prior existing catalog of VLP activity observed at Fuego Volcano, Guatemala.

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5 Long term stability of conduit dynamics at Fuego volcano, Guatemala, 2008-2015

5.1 Abstract

Repeating and near repeating seismic events in multiple bandwidths at Fuego volcano in Guatemala persisted for at least 8 years during the current ongoing eruptive episode which began in 1999. The long-lifespans of these signals implies a remarkable level of stability in the conduit system. Two separate classes of very long period events (100-10s) indicate pressurization within the shallow conduit prior to different types of explosions, while repeating long period events (0.5-5 Hz) reveal inter-explosion, small magnitude degassing with no visible emissions. We use these signals to inform an updated model of shallow conduit dynamics controlling explosive events from the years spanning at least 2008-2015.

5.2 Introduction

Open vent volcanoes provide unique opportunities for studying volcanic processes and present unique challenges for mitigating volcanic hazards (Rose et al., 2013). Whereas seismic precursors to eruptions at dormant volcanoes are common and often provide stark contrast to quieter, background seismicity (Chouet & Matoza, 2013; Randall White & McCausland, 2016), forecasting changes in behavior within an ongoing eruptive episode remains challenging and requires greater understanding of individual systems (Roman et al., 2016). Less than 1% of volcanic eruptions last longer than a decade (Siebert et al., 2011), and Fuego volcano in Guatemala began the 20th year of the current eruption in May 2019 (Global Volcanism Program, 1999). The ~3800 m basaltic to basaltic andesitic stratovolcano had 44 increases in activity levels classified as eruptions for the 2015-2018 calendar years by the Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología (INSIVUMEH), the agency charged with monitoring the volcano (INSIVUMEH, 2015, 2016, 2017, 2018). Only one of these increases in eruptive activity (referred to as paroxysms) involved loss of human life, but from the available instrumentation at Fuego, the activity on 3 June, 2018 was indistinguishable from “typical” paroxysms in the early hours of the event which would ultimately kill hundreds (Naismith et al., 2019; Pardini et al., 2019).

From at least 2005 through 2018, Fuego was seismically monitored by only one short-period station approximately 3 km southeast of the summit. Between 2008 and 2015, scientists from Michigan Technological University installed several temporary networks of broadband seismometers to provide snapshots of the activity during short time windows lasting days to weeks. Two distinct classes of events which were recorded only by the seismometers located within 1 km distance from the active vent show that the conduit system remained remarkably stable for all of the years covered by these shorter observation periods: long period (LP) events with signals between 0.5 and 5 Hz, and very

long period (VLP) events with signals between 100 and 10 seconds. We review previous work concerning Fuego seismicity during this period and introduce new data which support a model for the activity observed at the volcano.

5.3 Repeating Events

Recent work on seismicity at Fuego has focused on looking at VLP waveforms accompanying emissions from Fuego from 2008 through 2015. Emissions during that period initiated from two active vents at Fuego, named for their locations as a summit vent and a flank vent. VLP events coincident with emissions from specific vents corresponded to different emission types (Waite et al., 2013).

One of these event types (ashy, impulsive plumes from the summit vent in 2009) had previously been explored in detail by Lyons and Waite (2011). That work showed the most likely source to be a sub-vertical dike feeding a dipping sill that led to the summit vent. The VLP centroid is at the point those two features intersect 300 m west and 300 m below the summit vent. The modeled source time function showed that the sill inflated over for between 2 and 30 minutes, depressurized with an explosive emission, and inflated again. Further work to include the effects of tilt on the model generally agreed with this interpretation (Lyons et al., 2012; Waite & Lanza, 2016). Another one of the VLP event types from the classification scheme of Waite et al. (2013) was associated with ash-free degassing puffs from the summit vent in 2008. This activity was also examined by Nadeau et al. (2011) along with their observations of sulfur dioxide emissions during tremor episodes and inter-event degassing as well. Finally, slightly longer duration VLP events with ashy plumes initiating from the flank vent in 2008 showed a visibly different waveform when compared to the events coming out of the summit. In Chapter 4 we reported on data collected at the volcano in 2012 and noted that all three types of VLP events were still ongoing at Fuego, but that both vents were producing emissions and VLP signals associated with vent-specific activity in the preceding years.

Brill et al. (2018) reported on a suite of repeating LP events which occurred during 2012 and which were not associated with any visible emissions. In Chapter 3, we showed that these events were also present in the 2008 and 2009 data and were also recorded in shorter field experiments during 2014 and 2015. The modeling work in that chapter indicated a series of cracks around the conduit margin which opened and closed due to pressure buildup and release of gas rising from the magma faster than the magma itself, and the LP events themselves then show a lower energy type of degassing as opposed to tremor or explosive activity.

Figure 5-1. Fuego volcano aerial view showing the location of the permanent INSIVUMEH station (red triangle) and the location of the temporary seismic station in 2012, 2014, and 2015, which was also within ~200 m from the stations operated in 2008 and 2009. The lower inset shows a closeup of the two vents during the 2012 experiment.

5.4 Activity model

We can update the model of conduit dynamics slightly and expand the time range to which it can be applied. First, the VLP source from 2009 modeled by Lyons and Waite (2011) was still intact as of February 2015. Although in 2008 and 2009 each vent demonstrated differing emissions associated with unique VLP signals, during 2012 both

emission and VLP signal types initiated from both vents. We assert that both vents showing both types of activity requires that the conduit split feeding the individual vents be located above the VLP source centroid. The length of each vent's conduit and the depth at which they join is unknown, and possibly shifts over time (i.e. during lava flows or larger paroxysms), but the absolute positioning of the main vent has not wandered outside of an approximately 200 m radius as long as aerial images have been available (>40 years).

As magma passes from the dyke to the sill, the constriction and change of direction at the VLP source acts like a collection point for crystals and bubbles which have been forming during the ascent from depth while the liquid portions of the magma would pass through. This provides a point for the magma to cluster into portions, some of which are more volatile and crystal rich and some of which are more volatile and crystal poor. Spina et al. (2019) suggests that this organization could also be the result of changes in conduit diameter associated with a "roughness" within a conduit system as opposed to a smooth pipe often used in assumptions. The differential flow speeds of liquids around crystals was hypothesized at Fuego based on plagioclase crystal zoning by Anderson (1984). This sorting of the magma at shallow depths explains the clustering of explosive events and the more homogenous (Poisson) distribution of degassing events noted by Brill et al. (2018), and also agrees with findings by Castro-Escobar (2017) that several dominant processes control Fuego's explosions from November 2014 to March 2015.

The models proposed by Lyons and Waite (2011) and Nadeau et al. (2011) both invoked undercooling of Fuego magma due to the relatively high 5 wt % H₂O which allows the basaltic magma to behave like a more silicic magma would at shallow depths. Lyons and Waite (2011) estimated 80° C of undercooling at the VLP source depth and estimated 0.5-1 mm/h growth rates of plagioclase crystals at that temperature. These and other rapidly forming crystals would also force volatiles out of solution which would simultaneously increase the pressure in the sill. Lyons et al. (2012) assert that tilt measured using the seismic record preceded the more impulsive style of VLP eruptions by as much as 30 minutes, and Waite and Lanza (2016) incorporate the effects of this tilt directly into their source inversion process, which suggested a dipping pipe source below the summit as opposed to the spherical source from the forward modeling of Lyons et al. (2012). Shear along the conduit margin may also introduce a tilt as proposed for slowly ascending magma at Soufrière Hills volcano (Green et al., 2006) and Tungurahua (Neuberg et al., 2018).

As the magma continues to rise, the material transitions from melt-supported to crystal-supported between the VLP source and the surface. The viscosity of the magma increases enough that gas can no longer rise freely but is held in place as crystals and tight bubbles dominate, forming a "mush plug" similar to what Suckale et al. (2016) proposed at Stromboli. As in more silicic systems, shearing along the cooler conduit margins creates cracks along those interfaces (Tuffen et al., 2003), which allows at least some gas from further below in the system to escape to the surface (Gonnermann, 2015; Moitra et al., 2018). If gas supply is insufficient to keep the cracks open, they close, and due to the heat

in the system begin to anneal. As gas continues to percolate up through the system, local aggregations of gas eventually overcome the newly formed seals and generate the repeating LP events in a fashion like that modeled in laboratory experiments by Barth et al. (2019).

As this newly formed “mush plug” continues ascending, the material comprising it passes a brittle-ductile transition point. Eventually the shear forces within the plug or cap and the growing pressure within the pore spaces overcomes the strength of the magma itself and fragmentation occurs. How much pressure is contained prior to fragmentation and how far down into the magma in the conduit directly below the initiation point the fragmentation front propagates will be determined by the local concentration of crystals and bubbles which have aggregated along the flow path. This aggregation also will affect the explosion interevent timing, allowing for events which are spaced several minutes to several hours apart. In some instances, there will be enough gas content available locally to maintain open pathways through the plug, accounting for tremor which can also last on the order of half an hour to an hour or more. An important factor is that the broader (deeper) system supplies more or less steady inputs which only organize into explosion timing defining arrangements in the shallow system during these lower energy time periods.

Smaller events are not able to clear the newly fractured material from the conduit, and leave debris around the conduit top while larger events clear the volcanic throat more efficiently. This accounts for longer residence times of larger pyroclasts inferred from melt inclusions by Lloyd et al. (2013), as well as the lack of any sort of relationship between interevent time and event amplitude reported by (Brill et al., 2018). After the pressure is released, the system resets, fractures begin to anneal, and the magma continues advancing. In this model, small changes in magma supply rates from depth drive shifts between different activity regimes described over longer periods of time (Castro-Escobar, 2017; Escobar Wolf, 2013; Lyons et al., 2010; Naismith et al., 2019), allowing for lava flows and even paroxysmal activity without major changes needing to take place in the system. The causes of changes in supply rate from deeper in the system and possible early signs of these changes still require further investigation.

5.5 Summary and implications

Our updated model goes a long way towards explaining the variability within an otherwise remarkably stable, long term eruptive period at Fuego volcano. Within the 20 years of eruptive activity, these snapshots show a high degree of stability from 2008-2015 and offer details on how the volcano behaves between more energetic paroxysmal episodes. These repeating events were not visible on the INSIVUMEH operated station’s seismograms. This poses the question of whether these signals provide information valuable enough from a hazard mitigation standpoint about the ongoing state of the volcano to justify the greatly increased cost of installing and maintaining monitoring equipment close enough to the summit to capture them.

While the VLP signals are certainly dynamic and interesting from a scientific perspective, quantifying them in real time would have limited utility for hazard mitigation. For these, shorter monitoring periods lasting 24-72 hours once or twice a year to check for changes in waveform characteristics could be adequate to ensure no large changes in conduit shape have taken place. The cost associated with this type of monitoring would be much easier to absorb along with other field activities. The LP events might offer more information about how the system seals or doesn't seal over shorter time periods, and monitoring them would be extremely valuable if changes in those event rates were observed to change leading up to a paroxysm, but this has not yet been demonstrated. Due to the higher frequency content of these signals, they might not need to be monitored with broadband instruments, so cheaper instruments and even more importantly lower power consuming instrument configurations, could provide more attractive options.

Figure 5-2. Cartoon of eruption dynamics.

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