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Unusual Patterns of Seismicity during Eruptive and Non-eruptive Periods at the Persistently Restless Telica Volcano, Nicaragua

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Unusual Patterns of Seismicity during Eruptive and Non-eruptive Periods at the Persistently Restless Telica Volcano, Nicaragua

by

Melanie J. Rodgers

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy School of Geosciences College of Arts and Sciences University of South Florida

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Keywords: Volcano monitoring, phreatic eruption, low-frequency earthquakes, seismic event classification, multiplet analysis.

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DEDICATION

This work is dedicated to my family.

To my parents, Mike and Sandy, you taught me to follow my dreams and you believed in me every step of the way.

To my best friend, my hero and my brother, Simon, your footsteps will always guide me.

And to my sister-in-law, Meredyth, your love and laughter will always make me smile.
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ABSTRACT

Telica Volcano, Nicaragua, is a persistently restless volcano with high rates of seismicity that can vary from less than ten events to over a thousand events per day. Low-frequency (LF) events dominate the seismic catalogue and seismicity rates at Telica show little clear correlation with periods of eruption. As such, traditional methods of forecasting of volcanic activity based on increases in seismicity and recognition of LF activity are not applicable. A single seismic station has been operating at Telica since 1993, and in 2010 we installed a broadband seismic and continuous GPS network (TESAND network) at Telica. In this study we investigate the seismic characteristics surrounding a nine-month period of phreatic to phreatomagmatic explosions in 1999, and also from the initial three-and-a-half year deployment of the TESAND network, including a three-month phreatic Vulcanian eruptive period in 2011. We demonstrate that pertinent information can be obtained from analysis of single-station data, and while large seismic networks are preferable when possible, we note that for many volcanoes this is not possible. We find unusual patterns of seismicity before both eruptive periods; rather than a precursory increase in seismicity as is observed prior to many volcanic eruptions, we observe a decrease in seismicity many months prior to eruption. We developed a new program for cross-correlation of large seismic data catalogues and analysed multiplet activity surrounding both eruptive periods. We observed that the formation of new multiplets corresponds to periods of high event rates (during inter-eruptive periods) and high percentages of daily events that
belong to a multiplet. We propose a model for the seismicity patterns observed at Telica, where changes in seismicity are related to a cyclic transition between open-system degassing and closed-system degassing. Periods of open-system degassing occur during non-eruptive episodes and are characterised by high event rates, a broad range of frequency content of events and high degrees of waveform correlation. A transition to closed-system degassing could be due to sealing of fluid pathways in the magmatic and/or hydrothermal system, or due to magma withdrawal. Periods of closed-system degassing are characterised by low event rates, higher frequency contents and low degrees of waveform correlation. Eruptive periods may then represent a transition from closed-system degassing to open-system degassing, however the system must also be capable of transitioning to open-system degassing without eruption. These observations have important implications for volcano monitoring and eruption forecasting at persistently restless volcanoes. Rather than a precursory increase in seismicity as is often observed prior to eruption at other volcanoes, our observations indicate that phreatic eruptions at Telica occur after a decrease in seismicity, a corresponding change in the frequency content of events, and a decrease in waveform correlation. These changes may represent a period of closed-system degassing that could culminate in phreatic eruptions. The inclusion of real-time analysis of variations in frequency content and multiplet activity provides critical information for volcano monitoring institutions.
CHAPTER ONE:

INTRODUCTION

Seismic monitoring of volcanoes is a critical part of eruption forecasting (Sparks 2003). A suite of different seismic techniques is used routinely in volcano monitoring; for example, analysing changes in seismic event rate, monitoring variations in filtered or derived time series (e.g., RSAM, SSAM, and RSEM; Endo and Murray, 1991; Stephens et al., 1994; De la Cruz-Reyna and Reyes-Davila, 2001), analysing earthquake hypocentres, and identification of volcano-tectonic earthquakes (VTs), low-frequency (LF) earthquakes and volcanic tremor sequences (McNutt, 1996). Increases in seismicity rates are commonly observed as a precursor to eruption, and as such are a crucial aspect of volcano monitoring. For example, precursory seismic swarms, including LF swarms, were observed before the 1989-90 and the 2009 eruptions of Redoubt Volcano, Alaska (Power et al., 1994; Buurman et al., 2013). Precursory LF swarms were observed prior to the 1991 eruption of Mount Pinatubo, Philippines (Harlow et al., 1996), and precursory VT activity was observed prior to the 2006 eruption of Augustine Volcano, Alaska (Jacobs and McNutt, 2010). However, many volcanoes do not follow this precursory sequence of seismicity. Periods of seismic unrest do not always lead to eruptions (Moran et al., 2011); for example, neither a LF swarm in 2006 at Campi Flegrei Caldera, Italy (Saccorotti et al., 2007), nor
a seismic swarm in 1998 at Iwate Volcano, Japan (Nishimura and Ueki, 2011) culminated in an eruption. The opposite may also be true; volcanoes may erupt with very little seismic warning; for example, only five hours of seismicity preceded the 2008 eruption of Okmok Volcano, Alaska, (Johnson et al., 2010). Volcanoes that do not follow “typical” precursory seismic patterns remain a challenge for eruption forecasting and long-term monitoring.

From a monitoring perspective, persistently restless volcanoes (PRVs) (Stix, 2007) present a problem for volcano observatories and other monitoring agencies. PRVs typically have high and variable rates of seismicity, frequent explosions and persistent degassing. Much of volcano monitoring relies on detecting deviations from a ‘background’ or ‘normal’ level of activity. However, PRVs often sustain such a high and variable level of seismicity that no ‘background’ can be clearly identified, meaning that eruptions at PRVs are difficult to forecast on the basis of changes in event rates. Shishaldin Volcano, Alaska, has high rates of seismicity, persistent degassing and has had frequent explosions over the last two centuries (Nye et al., 2002). The 1999 sub-Plinian eruption of Shishaldin was preceded by a short-lived seismic swarm of ~ 60 events per day, but larger seismic swarms in the following years were not accompanied by eruptive activity (Petersen et al., 2006). Neither large variations in LF event rates at Ngauruhoe Volcano, New Zealand between 2006 and 2010, (Jolly et al., 2012), nor a swarm of over 2000 events per day at Turrialba Volcano, Costa Rica in 2001 (Tassi et al., 2004) were accompanied by eruptive activity. Telica Volcano, Nicaragua, is a PRV that has experienced small (VEI 1-2) eruptions every ~ 1-5 years since improved recording began in the 1970s (Siebert and Simkin,
The two most recent VEI 2 eruptions at Telica occurred in 1999 and in 2011, but seismicity rates at Telica show no clear correlation with eruptive activity and do not follow a typical pattern of precursory seismicity.

The aim of this dissertation is to characterise the patterns of seismicity surrounding eruptions at PRVs, and to gain insight into processes driving the transition between eruptive and non-eruptive periods at PRVs. We chose Telica as a representative PRV due to the prior catalogue of data and observations, frequency of explosions, ease of access and our department's long-standing collaboration with INETER (Instituto Nicaraguense de Estudios Territoriales). Chapter 2 of this dissertation presents an analysis of the seismicity surrounding the 1999 VEI 2 phreato-phreatomagmatic eruption of Telica. Only a single seismic station was operational during this eruption, but we show that analysis of single-station data is a powerful tool to characterise seismicity patterns at PRVs. In Chapter 2 we assess variations in daily seismicity rates, use spectral analysis to classify events and we perform cross-correlation analysis to identify and track families of repeating events. We find that there is a decrease in event rates before the eruption and before large explosive episodes during the eruption. We observe large variations in event rates and a sudden onset of families of repeating events, and we interpret the changes in seismicity as related to a transition from open-system to closed-system degassing.
In 2009-2010 we installed a broadband seismic and continuous GPS network (the Telica Seismic ANd Deformation network; or TESAND) on Telica. The seismic data analysed in Chapter 3 of this dissertation represents the culmination of the initial three-year deployment of the TESAND network. The network is still operational at the time of writing and will remain so for the foreseeable future. In May 2011 Telica erupted with a series of phreatic vulcanian explosions, and in Chapter 3 we also focus on the precursory and co-eruptive seismicity of this VEI 2 eruption. We detect events using a full-network detection method and also using a single-station approach, we analyse variations in daily event rates, we examine two different metrics for assessing the spectral content of events, we develop a classification system suitable for the wide range of event types that occur at Telica, and finally we locate a subset of events from a 20-month period surrounding the 2011 eruption. We observe highly variable seismicity rates and predominantly LF events and we find that similarly to the 1999 eruption, a decrease in seismicity occurs before the 2011 eruption. We again interpret these unusual patterns of seismicity as related to a transition from open-system to closed-system degassing. This interpretation is supported by multi-parameter observations (i.e., deformation, fumarole temperatures, SO$_2$ flow rates and eruption ash analysis (Geirsson et al., 2013)). However, we also observe periods of decreased seismicity without corresponding eruptive activity which suggests that the mechanism of transition must be able to change from closed-system to open-system degassing without a significant eruption, or that these periods do not represent a fully closed-system.
Identification and analysis of repeating families of earthquakes with nearly identical waveforms, often referred to as multiplet analysis, is a valuable tool for volcano seismologists, but routine analysis of large data catalogues is hampered by computational limitations associated with the cross-correlation of large numbers of events. The data catalogue analysed in Chapter 2 comprised over 29,000 events and the catalogue analysed in Chapter 3 comprised over 200,000 events. It is computationally unfeasible to directly cross-correlate this many events using existing tools, and so we developed a program ‘peakmatch’ to efficiently handle the cross-correlation of large seismic data catalogues. In Chapter 4 we describe the method behind peakmatch, and then apply peakmatch to three data catalogues: Initially we re-analysed the same data as used for the multiplet analysis in Chapter 2 to provide a direct comparison between the widely accepted two-stage method of Petersen (2007) and Thelen et al., (2010) and our method. We then applied peakmatch to an extended data catalogue from the 1999 eruption of Telica, and finally we analysed over 200,000 events from the three-year deployment of the TESAND network. We find that peakmatch performs extremely well for cross-correlation of large data catalogues, and has the potential to make multiplet analysis a routine part of seismic data analysis. We observe the onset of many new families of events before the decrease in seismicity before the 2011 eruption, and then during and after the eruption. We interpret the repeating events as related to magmatic and/or hydrothermal fluid flow and we suggest that the creation of many new multiplets may represent periods of open-system degassing, while periods with few new multiplets represent periods of closed-system degassing.
A single infrasound sensor was installed as part of the TESAND network. In Chapter 5 we present a preliminary analysis of infrasound and seismic data from some of the larger explosions of the 2011 eruption. We examine hourly seismicity rates before the three largest explosions and observe a two-hour decrease in seismicity before these explosions.

The research presented in this dissertation is a result of collaboration with co-authors, and use of the term ‘we’ throughout this work reflects the invaluable contributions of these co-authors. Chapter 2 has been published in the Journal of Volcanology and Geothermal Research (JVGR) (Rodgers et al., 2013). Chapter 3 will soon be submitted to JVGR. The methodology from Chapter 4 will be submitted to Computers & Geosciences, and the scientific results of Chapter 4 will be submitted to Seismological Research Letters. Most of Chapter 5 has been published in JVGR as part of a multi-disciplinary analysis of the 2011 eruption of Telica (Geirsson et al., 2013).

The results presented in this dissertation improve our understanding of the processes occurring at persistently restless volcanoes, such as Telica. Our model of the repetitive transition between open-system degassing and closed-system degassing is a hypothesis that can be tested with future work at Telica and also at other volcanoes, such as Shishaldin, Alaska; Ngauruhoe, New Zealand and Turrialba, Costa Rica. This research represents a step forward in our understanding of what drives phreatic eruptions at Telica, and provides a foundation for future seismic
monitoring at this volcano. The seismic event type classification approach presented in Chapter 3 can be easily adapted to any volcanic seismic data catalogue. The efficiency of this classification method makes it suitable for systematic application to large seismic data catalogues. In a similar way, our peakmatch program presented in Chapter 4 marks a significant improvement in multiplet analysis and allows for fast cross-correlation of large seismic data catalogues. Due to the efficiency of this program and its capability in handling large data catalogues in a short time period, peakmatch has the potential to be used for real-time monitoring applications. Its flexibility means that it can be easily adapted to the study of other time series data, such as GPS and infrasound, and is not limited to geophysical datasets.
CHAPTER TWO:

SEISMICITY ACCOMPANYING THE 1999 ERUPTIVE EPISODE AT TELICA VOLCANO, NICARAGUA.

ABSTRACT

Telica Volcano, Nicaragua, is a ‘persistently restless’ basaltic-andesite stratovolcano located in the Central American volcanic front. A high rate of low-frequency seismic events (LFs) has been recorded at Telica since the installation of a single, vertical-component 1 Hz seismic sensor (TELN) near its summit in 1993. Due to the high rate of LFs at Telica, traditional methods of forecasting volcanic activity based on increases in the overall rate of seismicity are not applicable; therefore an understanding of the nature of precursory changes in Telica’s seismicity is necessary to forecast future volcanic activity. In May 1999 a nine-month eruptive episode started at Telica, consisting of phreatic to phreatomagmatic explosions. Here we analyse over 29,000 seismic events recorded during a fifteen-month period of seismicity bracketing this eruptive episode, in an attempt to retrospectively identify precursory changes in seismicity. Seismic event rates between January 1999 and March 2000 show a reduction in the LF event rate three months before the onset of eruptive activity, closely followed by a short-lived swarm of high-frequency (HF) (> 5 Hz) events. After a three month data gap a second reduction in the LF event rate started in August 1999, directly following eruptive activity in
August and approximately two months before a series of explosions in October 1999. This reduction in the LF event rate was closely followed by a short-lived swarm of HF events that was coincident with the onset of numerous (22) short-lived, but populous, LF multiplets. A further reduction in event rate for both LFs and HFs is evident in the months between the October 1999 explosions and explosions on the 29th December 1999. We suggest that these changes in seismicity reflect a transition from open-system degassing to closed-system degassing at Telica and could signify a change in the volcanic system preceding future episodes of phreatic to phreatomagmatic activity at Telica and similar persistently restless volcanic systems worldwide. We note that these signals are for phreatic to phreatomagmatic activity and thus may not pertain to magmatic volcanism or to other persistently restless volcanoes prior to their magmatic activity.

2.1 INTRODUCTION

Current paradigms in eruption forecasting interpret the onset of low-frequency seismic events (LFS), or the appearance of LF swarms, as a short-term indication of impending eruption (Chouet 1996). For example, the generic volcanic earthquake swarm model of McNutt (1996) outlines a ‘generic’ precursory seismic sequence starting with a swarm of high-frequency (HF) earthquakes, followed by a peak rate in HF seismicity, a period of relative seismic quiescence, the onset of LF events, the onset of volcanic tremor (a sustained long-period signal), eruption, then post-eruption deep HF seismicity and then a decrease in seismicity. One of the key aspects of this model is the appearance of LF events as a short-term precursor, and such precursory LF
activity has often been observed immediately prior to many eruptions. For example, the 1989-90 eruption of Redoubt Volcano, Alaska, was preceded by 23 hours of LF seismicity (Stephens and Chouet, 2001), and the 1991 eruption of Mount Pinatubo, Philippines, was preceded by three days of increased LF seismicity (Harlow et al., 1996; Ramos et al., 1999). However, LF swarms that do not culminate in eruptions are also observed, for example, the 1998 seismic swarm at Iwate Volcano, Japan (Nishimura and Ueki, 2011) and the 2006 LF swarm at the Campi Flegrei Caldera, Italy (Saccorotti et al., 2007), yet they are less commonly documented (perhaps due in part to observational bias (Moran et al., 2011)). Despite the occurrence of LF swarms that do not culminate in eruptions, the observation of LF events, or LF swarms, remains crucial to many aspects of volcano monitoring and forecasting of eruptions.

A recognised style of volcanic activity, here termed ‘persistent restlessness’, is characterised by sustained high levels of geophysical and volcanic activity, including high or variable seismicity rates, strong degassing, and sporadic explosions. Volcanoes that exhibit persistent restlessness, here termed ‘persistently restless volcanoes’ (PRVs; also referred to as quiescently active volcanoes (Stix, 2007)), do not appear to experience the more typical distinct ‘background’ and ‘unrest’ states, but do experience distinct non-eruptive and eruptive phases that do not show a clear correlation with geophysical measurements. Based on the paradigm that high levels of LF seismic activity indicate an elevated short-term probability of eruption, PRVs present a challenge for forecasting because their varying level of seismicity makes traditional models of forecasting inapplicable. Hence understanding the nature of seismic precursors to eruptive episodes at PRVs is critical.
In this study, we investigate the seismic characteristics of the 1999 eruptive episode at the persistently restless Telica Volcano, Nicaragua (Figure 2.1). Telica is one of the most active volcanoes in Nicaragua and its historical activity has been dominated by Volcanic Explosivity Index (VEI) 0-2 eruptions (see Appendix A – Table A1, Siebert and Simkin, 2002). A phreatic to phreatomagmatic eruptive episode started in May 1999; explosions occurred intermittently throughout 1999 and 2000, and the eruptive episode ended in February 2000. Here we document pre-eruptive and co-eruptive changes in event rates, and co-eruptive changes in the size and number of LF multiplets. These observations suggest a distinct change in the character of seismicity surrounding the 1999 eruptive episode, however, seismic precursors to magmatic or larger eruptive episodes may not follow the pattern of seismicity observed during this eruption.

2.2 BACKGROUND

2.2.1 Persistently restless volcanoes

PRVs exhibit variable and often high levels of seismicity and other geophysical signs of unrest. Known PRVs range in composition from basaltic to andesitic, demonstrate a range of seismic activity patterns from near-continuous tremor to swarms of LF events, and have variable eruptive behaviour including Strombolian, phreatic-phreatomagmatic and sub-Plinian eruptions. Seismicity at basaltic PRVs; for example, Masaya, Nicaragua (Metaxian et al., 1997) and Villarrica, Chile (Palma et al., 2008), is typically in the form of tremor. Cyclic variations in
Figure 2.1. Location of Telica and of INETER seismic station TELN. Inset maps: (right) Central America and (left) major volcanic centres of Nicaragua.
gravity and gas flux have also been noted at Masaya (Williams-Jones et al., 2008). At basaltic-andesite or andesitic PRVs, such as Shishaldin, Alaska (Petersen et al., 2006); Gareloi, Alaska (Caplan-Auerbach and Prejean 2005); Poas, Costa Rica (Rowe et al., 1992); Turrialba, Costa Rica (Tassi et al., 2004); and Ngauruhoe, New Zealand (Jolly et al., 2012), high rates of discrete LF events are observed. An increase in seismicity from less than 100 events per day in January 2000, to over 2000 events per day in March 2001 was observed at Turrialba Volcano, Costa Rica, but was not accompanied by an eruptive episode (Tassi et al., 2004; Smithsonian Institution, 2001). The 1999 eruption of Shishaldin, Alaska was preceded by a short-lived seismic swarm of ~60 events per day; however, much larger seismic swarms of up to ~250 seismic events per day occurred in the following years with no subsequent eruption (Petersen et al., 2006).

PRVs often experience episodes of eruptive behaviour. Here we define an eruptive episode as a series of discrete explosions, which may or may not contain juvenile magma. While eruptive episodes at PRVs usually consist of periods of minor explosions, PRVs can also experience major sub-Plinian and Plinian eruptions. For example, at Masaya, Nicaragua, tephra deposits demonstrate sub-Plinian to Plinian eruptions dated to within the last 6 ka (Williams, 1983; Perez and Freundt, 2006; Costantini et al., 2009). However, it is unknown whether Masaya was also persistently restless at that time. The 1999 eruption of Shishaldin, Alaska, comprised both a Strombolian phase and a sub-Plinian phase, with eruption plumes up to ~16 km (Stelling et al., 2002; Vergniolle and Caplan-Auerbach, 2004). Visual observations of Shishaldin over the last two centuries suggest high levels of degassing and frequent small explosions, and seismic
monitoring since 1997 shows a variable seismicity rate (Nye et al., 2002), suggesting persistent restlessness at Shishaldin was present prior to the eruption and has continued up to the time of writing (early 2013).

2.2.2 Telica Volcano, Nicaragua

Telica volcano is a basaltic-andesitic volcano in the Central American volcanic arc, a chain of volcanoes extending from Santa Maria, Guatemala to Irazu-Turrialba, Costa Rica. Here the Cocos plate is subducting beneath the Caribbean plate at ~80 mm/yr (DeMets et al., 2010) and fore-arc sliver transport of ~10 mm/yr occurs in a northwest direction relative to the Caribbean plate (LaFemina et al., 2009). This fore-arc sliver transport may result either from oblique subduction of the Cocos plate, or from tectonic escape from the collision of the Cocos Ridge with the overriding Caribbean plate (LaFemina et al. 2009).

High rates of seismicity have been observed at Telica since the first seismometer was installed 0.4 km from the active vent in 1993, LF events are common and small explosions occur approximately once every 1-5 years. Monthly bulletins released by the Nicaraguan governmental volcano monitoring agency (Instituto Nicaraguense de Estudios Territoriales (INETER)), (Tenorio, 1993 onwards) report an average of ~3000 events per month between 1999 and 2002 (Figure 2.2) as detected by the summit station. The earthquake rate varies from less than ten events per day to over 500 events per day, but peaks in the seismicity rate are generally not correlated to eruptive episodes.
Figure 2.2. Monthly event rates from 1997 – 2002, reproduced from INETER monthly bulletins. For details on event detection parameters see Tenorio, 1993 onwards. Months for which there are no published data are indicated by asterisks under the time-axis. The time frame for this study is marked by a hashed box.

Other geophysical (gravity) and geochemical (gas) monitoring data also show Telica to be persistently restless. For example, microgravity measurements within 800 m of the crater show a net increase of up to 100 µGal between 1994-2000, suggesting a small mass increase at hundreds of metres depth (Locke et al., 2003). Although few measurements exist, the measured SO$_2$ flow rates from 1972 to 2003 vary between <40 Mg/day and 530 Mg/day (0.04 tons/day and 0.53 tons/day) without direct correlation to eruption (Mather et al., 2006).
2.2.3 The 1999 eruptive episode of Telica Volcano, Nicaragua

Low-explosivity vulcanian eruptions (VEI 1-2) are common at Telica and occur approximately every 1-5 years. Eruptive episodes have been documented since the 1970s and include eruptions in 1981-82, 1994, 1999, 2001, and in 2011 (see Appendix A – Table A1). In May 1999 a nine-month-long eruptive episode started at Telica (Figure 2.3). Small explosions and ash emissions were reported during the 21st-23rd May 1999, and on the 5th and the 20th June 1999. A significant explosion occurred on the 10th August that deposited ash ~20km away from the volcano and incandescence was observed in the summit crater of Telica on the 18th August 1999. The longest explosive period of this eruption occurred from the 3rd-15th October 1999; on the 5th October 1999 INETER staff reported seeing ash and lava bombs within the crater and on the 11th October 1999 a large explosion was reported. The second longest explosive period occurred from the 17th-24th November 1999 and there were reports of a large explosion and noises similar to gunshots on the 17th November 1999. Explosions occurred on the 29th December 1999 with ash plumes reaching between 1 – 5 km and ash deposition up to 45 km away. Small explosions were reported on the 13th January 2000 and ash and gas emissions were reported to occur until the 17th February 2000. Here, we consider the start of the eruptive episode as the 21st May 1999 and the end as the 17th February 2000 (Tenorio, 1999; 2000; Smithsonian Institution, 1999; 2000a; 2000b).
2.3 DATA ANALYSIS

2.3.1 Seismic data

The data analysed in this study come from a single, short-period (1 Hz), one-component (vertical) seismometer (Mark Products L-4 sensor) operated by INETER. The instrument is located in a concrete hut at station TELN, situated ~0.4 km east of the crater rim (Figure 2.1). Continuous data were recorded at 100 Hz, were telemetered to INETER and processed using SEISLOG (Utheim and Havskov, 1997) and WILLY LEE (Lee et al., 1998) to automatically detect seismic events. Waveforms were only saved for detected events. For further details on seismic data acquisition and processing, see Tenorio, 1999.
The seismic catalogue used in this study starts on the 1\textsuperscript{st} January 1999, approximately five months before the onset of the eruptive episode, and finishes on the 31\textsuperscript{st} March 2000 (Figure 2.2). On the 14\textsuperscript{th} March 1999 and on the 13\textsuperscript{th} December 1999 the gain was changed on all seismometers at INETER. These gain changes had no effect on the event detection method. There is a three-month gap in the data, due to a loss of archived data, between 13\textsuperscript{th} May 1999 and 16\textsuperscript{th} August 1999. Unfortunately this data gap surrounds the onset of the eruptive episode at Telica on the 21\textsuperscript{st} May 1999 and surrounds the 10\textsuperscript{th} August 1999 explosive activity. Other small data gaps occur throughout the catalogue, either from station outages or from data loss, most notably as intermittent periods during November and December 1999 (Figure 2.3). The waveform catalogue of 29,710 events was obtained by INETER in real time and only waveforms of detected events were archived, hence continuous waveform data were not available for this study.

\textbf{2.3.2 Data analysis overview}

Due to the limited data available, that is single-station short-period event-detected data, we are constrained as to the type of analyses that can be performed. Events cannot be located using a single station. However, analyses such as the temporal variation in amplitude and in rates of events classified by spectral content provide simple but useful means to characterise the seismic activity observed at the site. Waveform cross-correlation is also possible with single-station data (Petersen 2007). The identification of families of repeating events (multiplets) suggests that the events have similar locations, and the temporal evolution of multiplets can provide insight into the processes occurring at Telica.
2.3.3 Spectral and amplitude analysis

A simple stand-alone automatic event classification algorithm, AECAP (Powell, 2004), was used to calculate the spectral and amplitude information. The three peak frequencies of each event in the INETER seismic catalogue were calculated (Figure 2.4) based on the spectra of the entire waveform (100 seconds). The three largest amplitude peaks in the frequency domain in the range 1 to 15 Hz were then identified as the three dominant frequencies of the event (Figure 2.4). Approximately 50 events were inspected by hand to verify the peak frequencies identified by AECAP. In the time domain the peak amplitude was measured after removing the mean of the waveform (to correct for any offset waveforms).

A fundamental assumption of AECAP is that the spectrum of every event can be characterised by three peaks. Based on our verification, the three dominant spectral peaks are identical or similar for a monochromatic event (Figure 2.4a). For events with broad spectra, the three differing dominant frequencies are due either to one broad frequency peak, or due to three (or more) distinct spectral peaks in the event's spectral density function (Figure 2.4b and 2.4c).

2.3.4 Event classification and event rates

We sought to formulate a systematic and internally-consistent event classification scheme for Telica based on the information returned by AECAP (three dominant peaks per event) and the characteristics of Telica's seismicity based on visual inspection of event waveforms. Because we
Figure 2.4. Waveforms, spectrograms and periodograms of selected events. Spectrograms produced using a window size of 2s, overlap of 0.99s and FFT size of 512 (values chosen from program defaults). a) Low-frequency event with dominant spectral energy at 2 Hz, from 16th August 1999, b) High-frequency event with dominant spectral energy at 7 Hz from 10th September 1999, c) Mixed-frequency event with spectral energy peaks at 3 Hz and 6 Hz from 1st February 1999.
were only able to examine waveforms on one seismometer (i.e., limiting our ability to inspect an event on multiple stations to rule out path effects, or identify whether or not events have mixed first motions) we choose to avoid traditional volcano-seismic event classification schemes (e.g., VT, LP) in this study; reclassification of Telica's seismicity based on a broader analysis using multi-station data from a recently-deployed broadband network will be the subject of a future study (see Chapter 3). Here, using a threshold frequency of 5 Hz (Lahr et al., 1994) seismic events were classified as LF events (all three peak frequencies < 5 Hz), HF events (all three peak frequencies > 5 Hz), or mixed-frequency (MF, a mixture of > and < 5 Hz) and daily event rates for LF, HF and MF events were determined. The 5 Hz threshold frequency is based on detailed analyses of seismicity at volcanoes such as Redoubt, Alaska (Lahr et al., 1994), but is ultimately an arbitrary cut-off for Telica. Furthermore, our choice to use the top three spectral peaks for classification purposes is also arbitrary, but is meant to attain a balance between too little information from using only a single dominant spectral peak and the classification being overwhelmed by using many smaller spectral peaks.

2.3.5 Multiplet analysis

The seismic catalogue used for multiplet analysis consists of 16,443 events from the 16th August 1999 to the 31st March 2000 and represents a seven-and-a-half-month period surrounding the energetic explosions of the 1999 – 2000 eruptive episode. Because of the three-month data gap between May and August 1999 and the lack of data from the onset of the eruption, we chose to focus solely on the period of data that would allow us to investigate multiplet activity immediately surrounding the explosive activity.
Given the number of events recorded it was not computationally feasible to cross-correlate all events with each other, therefore the two-stage method of Petersen (2007) and Thelen et al. (2010) was used. The length of individual events varied but was typically 10-20 seconds in duration. Because events in the catalogue contained no pick information and because arrival times varied considerably within the waveform, a 40 s window was used to ensure the entire event was captured. Events were filtered between 0.5 – 10 Hz before cross-correlation. Waveform cross-correlation was carried out using the Matlab GISMO suite (Reyes and West, 2011). The first stage of this process was to cross-correlate all events within a 24 hr period to produce a daily cross-correlation matrix. Next, a master event in this matrix was determined by finding the event with the maximum mean cross-correlation value (i.e., the maximum mean row value within the matrix). Any event on the same day that correlated with the master event at a value greater than or equal to the threshold value of 0.7 (see threshold discussion below) was considered to be part of the same family of events and this event was then added to the family and removed from the matrix. All events with cross-correlation values above the threshold value were added to the family and removed from the matrix until no more events correlated with the master event above the threshold value. A family could contain as few as two events and there was no upper limit on the number of events in a family (our largest daily family contained ~60 events). The master event was then removed from the matrix and the processes repeated until no more families remained in the matrix. Rather than using only the master event for further analysis we then stacked all the events in each individual family to produce one stacked event per family. The stacking process improved the signal-to-noise ratio of the event and produced a single event that represented an entire family. In total 291 stacked
families were produced for the entire data set. On some days no families were identified, while
on other days there were as many as 14 families.

In the second stage of the cross-correlation process all 291-stacked families were cross-
correlated with each other to produce a final cross correlation coefficient matrix. To find
multiplets in this final cross-correlation matrix we employed a process similar to the first stage,
in which the maximum mean cross-correlation value was used to determine a master event
and, using a cross-correlation threshold of 0.8 (see threshold discussion below), all events
correlating with this master event (i.e., a stacked family) were deemed to be part of the same
multiplet (Petersen, 2007; Thelen et al., 2010). Daily stacks that did not correlate with any other
daily stacks were not considered to be multiplets, meaning a multiplet must contain a minimum
of four events. While this method is capable of dealing with large volumes of data, it will only
detect multiplets containing events that occurred more than once a day, and any multiplet
consisting of events occurring either within one day, once a day, or more infrequently, even
over a long period of time, would be missed.

The initial threshold value of 0.7 was chosen by visual comparison of the individual waveforms
in families produced at different threshold values. Master events from various sample days
were chosen and families identified using cross-correlation thresholds of 0.6, 0.7 and 0.8. Figure
2.5 shows a threshold test using a master event from the 16th August 1999. For a threshold of
0.8 no events were identified as part of this family, at a threshold of 0.7 three events were
identified as part of this family and are visually similar (Figure 2.5a). At a threshold of 0.6, 34
events were identified as part of the family, but show less similarity throughout the waveform (Figure 2.5b). For many of the sample master events too low a threshold value created very large families with little waveform similarity between events, and too high a threshold value produced very few family members and missed obviously similar events. A threshold of 0.7 was chosen for the first stage in the process as it allowed identification of a sufficiently high number of events while ensuring the events were sufficiently similar. A higher threshold of 0.8 was chosen for the second stage as the daily events were stacked and therefore had a better signal-to-noise ratio. The threshold values used were the same as those used by Thelen et al. (2010), however, correlation of events above the threshold value will be influenced by noise and threshold values are not directly comparable between seismic networks.

2.4 RESULTS

2.4.1 Event classification and event rate results

Histograms of daily event rates are plotted for LF events, HF events and MF events (Figure 2.6). LF events dominate the seismic catalogue (Figure 2.6a). Of the 29,710 total events, 25,648 are classified as LF events and there are on average 80 LF events per day during the study period. HF events are therefore less common than LF events at Telica; only 810 events are classified as HF, with an average of 2.5 HF events per day (Figure 2.6b). MF events account for 3252 of the total events and there are on average 10 MF events per day (Figure 2.6c). Both the LF and MF event rates show a high variability, whereas the HF events rates show a few discrete peaks
Figure 2.5. Waveforms of a sample master event (plotted in black) from the 16\textsuperscript{th} August 1999 with two other waveforms (blue and red) that have cross-correlation values of \textbf{a) 0.7} and \textbf{b) 0.6} respectively.

within the otherwise low event rates. We subdivide the histograms in Figure 2.6 into three phases based on changes in activity at the vent: Phase 1 occurs before the onset of the eruptive episode on 21\textsuperscript{st} May 1999; Phase 2 occurs during the eruptive episode from the 21\textsuperscript{st} May 1999 – 17\textsuperscript{th} February 2000; and Phase 3 occurs after the eruptive episode, from the 18\textsuperscript{th} February 2000 onwards.
Figure 2.6. Daily event counts for the three classifications used in this study. a: Frequency peaks below 5 Hz (LF events). b: Frequency peaks over 5 Hz (HF events). c: Frequency peaks both above and below 5 Hz (MF events). Note the order-of-magnitude difference in vertical scale between the LF histogram (a) and the HF histogram (b). Explosive periods are marked by grey boxes/vertical lines and periods with no data are marked by diagonal shading. Dates of station gain changes (14th March 1999 and 13th December 1999) are marked with arrows.
In January 1999 (Phase 1), before the eruptive episode, LF event rates (Figure 2.6a) increase to a maximum of 459 events on the 26th January 1999. LF events then decline throughout February and March 1999, reaching a minimum of zero events per day in the middle of March 1999. Note that the gain change occurs on the 14th March 1999 and that the event rate minimum occurs immediately after; however, given the steady decline in events from January 1999 onwards, we believe this to be a real reduction in event rates. If the change in event rate was due to a change in event detection parameters as a result of the gain change on the 14th March 1999, we would expect to see a sudden change in event rates on this day rather than a steady decline during the previous month. During Phase 1 HF event rates (Figure 2.6b) vary from 0-26 events per day with a 3-day peak in HF event rates on the 10th March. In Phase 1 MF event rates (Figure 2.6c) reach a maximum of 77 events on the 31st January 1999, at a similar time (i.e., offset by five days) to the LF peak rate. Similarly to the LF events (Figure 2.6a), the MF event rates (Figure 2.6c) decrease throughout February and March 1999 and reach a minimum after the gain change on the 14th March 1999.

Data during Phase 2 were not available until August 1999, three months after the onset of the eruptive episode in May 1999. In August 1999 the LF event rate was initially high (up to ~400 events per day) following the August explosions. The event rate gradually decreased throughout August and September 1999 and LF events finally ceased on the 19th October 1999, following the October explosions. In the two-month period between the end of the October 1999 explosions and the December 1999 explosions very few LF events occurred, with the exception of a small (≤20 events) increase and decrease 6 days before the November 1999
explosions. This reduction in LF event rate could be attributed to tremor saturating the record and obscuring discrete LF events, but it is not possible to verify this due to the lack of continuous waveform data. Real-Time Seismic Amplitude Measurement (RSAM) (Endo and Murray, 1991) plots from January 1999 to March 2000 were reproduced from published INETER bulletins (Tenorio, 1999, 2000) (Figure 2.3) (Note that data gaps in the event detected catalogue come from a loss of archived data rather than station outage and that RSAM values were recorded in the published INETER bulletins). These plots suggest that RSAM does not increase during the periods when the LF event rate decreases, and therefore the apparent reduction in LF event rates is likely not the result of high-amplitude tremor saturation. Several small week-long swarms of less than 20 LF events per day occurred during this period (Figure 2.6a), although station outages hamper our ability to know how common these were. There was no obvious increase in LF events before the November or December 1999 explosions, although one of the small week-long swarms occurred approximately two weeks before the December 1999 explosions. After the December 1999 explosions the LF events spiked in short-lived swarms of 150-200 events per day lasting for ~3 days and recurring approximately every week throughout January 2000. In mid August 1999 there were no HF events before the onset of a short-lived HF frequency swarm on the 30th August 1999. The swarm then lasts for approximately 14 days and the peak rate of HF events (22 events/day) occurs on the 6th September 1999 before dropping to zero events on the 13th September 1999. The LF event rate then settles at less than five events per day before the October, November and December 1999 explosions; however this period is affected by station outages. On the 6th January 2000 a small swarm of HF events occurs, with a maximum high-frequency event rate of 12 events per day,
possibly associated with the explosive activity on the 13\textsuperscript{th} January 2000. MF event rates remain low in Phase 2, in contrast to the LF event rates which return at a high rate. There is an isolated peak of \(~20\) MF events per day at the end of August 1999, coincident with the HF swarm. MF rates start to gradually increase in December 1999, reaching a peak of 63 events on the 22\textsuperscript{nd} January 2000 before decreasing.

In Phase 3 the LF event rate continues to decline from \(~150\) events per day and reaches \(~50\) events per day by the end of the study period on 31\textsuperscript{st} March 2000. The HF event rate decays after the peak in late January and by the start of Phase 3 has reached rates of 0-2 events per day, which persists until the end of the study period. The MF event rate decreases from \(~20\) events per day at the beginning of Phase 3 to 1-2 events per day by the end of the study period.

2.4.2 Amplitude results

The peak amplitude of each event is plotted in Figure 2.7. There is considerable scatter in the plot, and the gain change on the 14\textsuperscript{th} March 1999 and on the 13\textsuperscript{th} December 1999 can clearly be seen by the step changes in the maximum of the peak amplitudes. Within the scatter some structure can be seen in the overall trend of the peak amplitudes. In January-February 1999 there is an overall decrease in the peak amplitude. In August 1999, after the 3-month data gap the events return with larger amplitudes than before the data gap, but then again decrease in amplitude during August and September 1999. Another trend in decreasing amplitude can be seen in January-February 2000. Due to the changes in gain it is impossible to directly compare
amplitudes across the study period; however the plot strongly suggests temporal amplitude changes within each of the three different gain periods.

![Figure 2.7](image)

**Figure 2.7.** Time series showing the peak amplitude for all events in the INETER catalogue between the 1\textsuperscript{st} January 1999 and the 31\textsuperscript{st} March 2000. Explosive periods are marked by grey boxes and periods with no data are marked by diagonal shading. Dates of station gain changes (14\textsuperscript{th} March 1999 and 13\textsuperscript{th} December 1999) are marked with arrows. Note the change in peak amplitudes associated with the gain changes.

### 2.4.3 Multiplet results

To identify families of earthquakes cross-correlation analysis was carried out. Thirty-seven multiplets created from the 291 daily-stacked families were found to contain a cumulative total of 1770 individual events. The cross-correlation coefficient matrix (Figure 2.8) shows cross-correlation values of all 291 stacked families cross-correlated against each other. A multiplet timeline (Figure 2.9) represents the activity of each of the 37 multiplets over time. Each diamond on the timeline represents when a single event within the multiplet occurs, and the
percentage of the total multiplet events (1770) that occur in each multiplet displayed next to the multiplet. Multiplet sizes ranged from 4 events, the minimum necessary to be identified as a multiplet (multiplet no. 29, Figure 2.9), to 283 events (multiplet no. 19, Figure 2.9). Of the 37 multiplets identified during this eight month period, all but one (multiplet no. 13, which contained 11 events, Figure 2.9) had peak spectral energy below 5 Hz and thus can be classified as LF events.

**Figure 2.8.** Cross correlation matrix for stacked events in the period of 16\textsuperscript{th} August 1999 – 31\textsuperscript{st} March 2000. The eruptive episode ends on the 17\textsuperscript{th} February 2000.
Figure 2.9. Timeline of multiplets from 16\textsuperscript{th} August 1999 to 31\textsuperscript{st} March 2000. Each horizontal line represents a multiplet and each diamond on the line represents a single event within the multiplet. The percentage of events in the multiplet with respect to total events in all multiplets is displayed before each multiplet. Explosive periods are marked by grey boxes and periods with no data are marked by diagonal shading.
The multiplet analysis starts mid-way through Phase 2, after the onset of the eruptive episode, and shows distinct temporal changes in multiplet activity (Figure 2.9). The first distinctive change in multiplet activity occurs on the 29th August 1999, when new short-lived multiplets start to appear. Before this, four multiplets were active; events in those four multiplets together make up 7.5% of the total multiplet activity (Figure 2.9), but we note that some of these multiplets persist beyond the 29th August 1999. The cross-correlation coefficient matrix (Figure 2.8) shows a high degree of cross-correlation for daily stacks that occur before the 29th August 1999. Between the 29th August 1999 and the start of the explosions on the 3rd October 1999, 22 new multiplets switch on; these 22 multiplets comprise 72% of the total multiplet activity (Figure 2.9). These multiplets are short-lived and nearly all of the multiplets that appeared during this five-week period had switched off by the end of the explosions (on the 15th October) and did not return within the study period. Three multiplets (No. 10, 16 and 17, Figure 2.9) are switched off during the October explosions. The most populous multiplet of the study period (multiplet no. 19, comprising 16% of multiplet activity (Figure 2.9; 2.10)) occurs during this time, and is active for five days. Between the 3rd October 1999 and the end of the eruptive episode on the 17th February 2000, nine new multiplets switch on; these multiplets make up 19.4% of the total multiplet activity (Figure 2.9); however, the majority of this percentage is comprised of events in multiplet 34 (Figure 2.9; 2.11) which accounts for 12.2% of the total multiplet activity. This dominant multiplet persists beyond the end of the eruptive episode and continues until the end of the study period. Between the end of the eruptive episode on the 17th February 2000 and the end of the study period on the 31st March 2000, two new multiplets switch on; these two multiplets make up 1.6% of the total multiplet activity.
(Figure 2.9). However, multiplet 34 (Figure 2.11) and 35 remain active during this period and by including the events from these two multiplets that occur after the 17th February 2000 then the multiplet events in this period make up 8.4% of the total multiplet activity. The cross-correlation coefficient matrix (Figure 2.8) shows a high degree of cross-correlation for daily stacks that occur during this post-eruption period, indicating that the events that occur within this period are highly similar, which can be explained by the dominance and long duration of multiplet 34.

Figure 2.10. a) Waveform (top), spectrogram (left bottom), and b) periodogram (inset) of stacked waveforms for multiplet 19 (Figure 9), the largest group of events in the eruptive episode. The multiplet is active from the 11th - 15th September 1999 and contains 283 events. Spectrogram produced using a window size of 2s, overlap of 0.99s and FFT size of 512.
Figure 2.11. a) Waveform (top), spectrogram (left bottom), and b) periodogram (inset) of stacked waveforms for multiplet 34 (Figure 9), the largest group of events from the post-eruptive episode. The multiplet is active from the 18th January 2000 until the end of the study period on the 31st March 2000 and contains 216 events. Spectrogram produced using a window size of 2s, overlap of 0.99s and FFT size of 512.

In total 16,443 events occurred at Telica between the 16th August 1999 and the 31st March 2000, of which 1770 (~10%) are considered to be part of a multiplet. The total number of events considered part of a multiplet is entirely dependent on the choice of cross-correlation threshold (see section 2.3.5). An alternative way to view percentage is to look at the daily variations of the percentage of the total daily events that are part of a multiplet (Figure 2.12). In the period before the 29th August 1999, 3.8% of the total events during this period are part of a multiplet (Figure 2.12). In the period between the 29th August 1999 and the start of the explosions on the 3rd October 1999, 44.5% of the total events are part of a multiplet. This
percentage reaches a maximum of 94% on the 11\textsuperscript{th} September 1999 (Figure 2.12), (i.e., almost every event of the 215 events that occurred on the 11\textsuperscript{th} September 1999 belonged to a multiplet). In the period between the 3\textsuperscript{rd} October 1999 and the 17\textsuperscript{th} February 2000, 4.2\% of the total events are part of a multiplet; however, this percentage increases in the month before the December explosions, with a maximum of 75\% on the 28\textsuperscript{th} December 1999, the day before the explosions on the 29\textsuperscript{th} December 1999 (Figure 2.12). In the post-eruptive period from the 18\textsuperscript{th} February 2000 to the 31\textsuperscript{st} March 2000 only 3.8\% of the total events are part of a multiplet.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{multiplet_percentages.png}
\caption{Percentage of daily events occurring as part of a multiplet (black diamonds). Explosive periods are marked by grey boxes and periods with no data are marked by diagonal shading.}
\label{fig:multiplet_percentages}
\end{figure}
In summary, three notable changes in multiplet activity are evident from our analysis. Firstly, in the period from late August to just before the October 1999 explosions there is a sudden onset of many (22) new short-lived, but populous, multiplets that comprise the majority of the multiplet activity (Figure 2.9), while the percentage of events that belong to a multiplet is high during this period (Figure 2.12). Secondly, multiplet activity before the December 1999 explosions does not exhibit an onset of many multiplets (Figure 2.9), as seen before the October 1999 explosions, but does see an increase in the percentage of events that belong to a multiplet (Figure 2.12). Thirdly, in the post-eruptive period one multiplet comprises most of the multiplet activity in the post-eruptive period (Figure 2.9).

2.5 DISCUSSION

LF seismicity is a common short-term precursor to volcanic eruptions. For example, the 1989-90 eruption of Redoubt, Alaska, was preceded by ~23 hours of increased rates of LF seismicity that occurred after a quiescent period of 23 years (Stephens et al., 1994; Chouet et al., 1994). Precursory LF swarms have also been observed at Galeras, Colombia, during the 1991 eruption (Cruz and Chouet, 1997), at Nevado del Ruiz, Colombia, in the months preceding the 1985 eruption (Martinelli, 1990) and at Mount Pinatubo, Philippines, before the VEI 6 eruption in 1991 (Ramos et al., 1999). However, development of forecasts based on LF seismicity rates at PRVs, such as Telica, is difficult given the a-typical pattern of seismicity (e.g., Figure 2.6). The maximum rate of LF seismicity observed during this study period was 459 events per day on the 26th January 1999 (Figure 2.6a), four months before the onset of the eruptive episode, but LF event rates from August 1999, mid-way through the eruptive episode, reach almost the same
level (434 events per day on the 17\textsuperscript{th} August 1999) as those in January 1999 (Figure 2.6a).
Forecasting eruptions at Telica cannot rely on an increase in rate of LF events as a precursor to volcanic activity as LF rates are highly variable, and the data suggest a precursory drop in LF seismicity before the onset of the eruptive episode and before the most energetic explosions, although we note that a precursory drop in seismicity is not observed before every explosion.

LF events at open-vent volcanoes such as Telica may be attributed to resonance of a magmatic and/or hydrothermal fluid cavity. In these fluid related models, LFs, often referred to as long-period (LP) events are generated at the fluid-solid boundary in response to a trigger, which sets up a wave at the fluid-solid boundary (Chouet, 1988; 1996; Neuberg 2000). The seismic energy is then trapped within the fluid by the high impedance contrast between the fluid and solid, setting up a resonance and generating the low-frequency wavefield in the elastic medium. While resonance of a fluid-filled cavity is generally accepted as the origin for the low-frequency wavefield, the trigger for the resonance is less well understood. At systems such as Telica, which exhibit high levels of degassing (Tenorio, 1993), magmatic/hydrothermal fluids are a plausible source for LF seismicity (Chouet and Matoza, 2013). Models such as the “pressure cooker” model, where periodic depressurisation of hydrothermal fluids in a crack triggers resonance (Nakano et al., 2003), or the “choked flow” model, where flow past a constriction in a crack causes fluid to accelerate to supersonic speeds, thereby choking the mass flow and generating a shock wave downstream of the constriction (Chouet et al., 1994; Morrissey and Chouet 1997) could both trigger LFs at the high event rates observed at Telica.
Assuming magmatic and/or hydrothermal fluid movement is the source of LF seismicity at Telica, the changes in seismicity at Telica could relate to changes in the fluid circulation system and transitions between open-system and closed-system degassing. The decrease in LF seismicity in February-March 1999 and in August-September 1999 (Figure 2.6a) may be attributed to a breakdown of the fluid circulation system and a transition from open-system to closed-system degassing. The decrease in LF events could be caused by the sealing of cracks and degassing pathways, possibly due to mineralisation or clogging of pathways. Given the low rate of LF seismicity during late October, November and December 1999, we suggest that sealing of the degassing system was more extensive than before the October 1999 explosions, allowing almost no degassing to occur. The decrease in LF rates at the end of the study period continues throughout 2000 (Figure 2.2) and culminates in explosions in January 2001 (Tenorio, 2001). Post-explosion increases in LF seismicity after the August 1999 activity and after the December 1999-January 2000 activity would be consistent with a cyclic transition between open-system and closed-system degassing, whereby sealing of an open-system leads to a closed-system, which then transitions to an open-system during explosions and then seals itself again.

The activation of 22 new multiplet sources (Figure 2.9) during the period of decreasing LF activity before the October explosions, could relate to the formation of new degassing pathways in response to sealing of the pre-existing degassing pathways. Not only is this the largest onset of new multiplets during the study period, but these multiplets contain the greatest number of events within the study period. These multiplets are rapidly discontinued,
which suggests the new pathways are not stable and are destroyed quickly. The increase, before the October 1999 explosions, in the percentage of total daily events that are part of a multiplet (Figure 2.12), suggests a focusing of nearly all degassing activity through these newly created degassing pathways and suggests that the pre-existing degassing pathways were destroyed or sealed. An increase in the percentage of total daily events that are part of a multiplet also occurs before the December 1999 explosions, but unlike before the October 1999 explosions, there is no activation of many new multiplets before the December 1999 explosions. The overall number of events during December 1999 is considerably lower than during October 1999 and the high percentages in Figure 2.12 could be caused by focusing of all the degassing through the few pathways that were active at the time, rather than the creation of new degassing pathways. The dominance of one multiplet from January 2000 onwards suggests the creation of a new and dominant degassing pathway and a possible return to open-system degassing.

The onset of HF seismicity immediately after the onset of the decrease in LF seismicity in February-March 1999 and in August-September 1999 (Figure 2.6) may also be attributed to a transition from open-system to closed-system degassing. If the HF volcanic seismicity reflects shear failure of rock in response to stress changes (Lahr et al., 1994; Roman and Cashman, 2006), either such stress changes could have been caused by increased fluid pressures within a recently sealed hydrothermal system, or higher fluid pressures could lower the effective normal stress and promote shear failure (Byerlee, 1978) on local faults at Telica. Alternatively, the HF events in October 1999 that are coincident with the activation of new multiplets (Figure 2.9)
could reflect the opening of the new gas pathways responsible for generating the multiplets. Assuming these HF events reflect the opening of new gas pathways, if the new pathways were able to adequately degas the system, a contemporaneous increase in LF events would be expected. However, an increase in LFs is not observed during or after the HF swarm, suggesting that these new pathways are not sufficient for open degassing, and that despite the focused degassing through these new pathways, as seen by the high percentage of multiplet activity (Figure 2.12), the system remained mostly sealed.

Multiplet studies are common for lava-dome eruptions, such as Bezymianny, Russia; Mount St Helens, USA and Soufriere Hills Volcano, Montserrat (West 2013; Thelen et al., 2011; Green and Neuberg 2006), but are less common for eruptions at low-viscosity systems. Studies of lava-dome eruptions interpret precursory multiplets as related to a gas-charged closed-system degassing regime (Thelen et al., 2011). Multiplet swarms were identified at Shishaldin, Alaska, during non-eruptive periods and have been interpreted as choked flow of gas (Chouet et al., 1994) in the hydrothermal system (Petersen 2007). Given the similarity of seismicity and volcanic activity at Telica and Shishaldin we find this interpretation a plausible source mechanism for multiplet and LF activity at Telica and it is compatible with our interpretation of focusing of seismicity into few degassing pathways in response to the transition from open-system to closed-system degassing.
2.6 CONCLUSIONS

We examined seismic spectral characteristics over a fifteen-month period surrounding the 1999 eruptive episode at Telica volcano, Nicaragua, using waveform data from a single long-running seismic station. Approximately three months before the onset of eruptive activity in May 1999, a decrease in LF events (<5 Hz) occurred, followed by a HF (>5 Hz) earthquake swarm. Another decrease in LF events occurred in August-September 1999 following the August explosions, which was again followed by a HF earthquake swarm. This HF swarm was coincident with the onset of many short-lived, populous LF multiplets in the month before a series of explosions in October 1999. Following the October 1999 explosions, LF seismicity was low and remained low surrounding a series of explosions in November 1999 and in the period before explosions on the 29th December 1999. These observations have important implications for seismic monitoring and eruption forecasting at Telica and similar volcanoes and demonstrate that pertinent information on eruption precursors may be obtained from a single short-period instrument.

Typical seismic precursory patterns, such as a short-term increase in the rate of LF seismicity, are generally not observed at PRVs (e.g. Telica), and other approaches to forecasting eruptive behaviour at these volcanoes must be used. A reduction in LF seismicity rates, the onset of HF swarms and the onset of swarms of repeating LF events could be key indicators of physical changes, such as the closing of gas and fluid pathways and a transition from open-system to closed-system degassing; and while these observations do not occur before all explosions they may be useful in forecasting activity at Telica. These seismic observations relate to phreatic-to-
phreatomagmatic activity and as we have only sampled a short time period where complex volcanic processes are at work, our conclusions may not be appropriate for magmatic volcanism at Telica or at other persistently restless volcanoes.

2.7 ACKNOWLEDGEMENTS

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CHAPTER THREE:

HIGH RATES OF SEISMICITY AT THE PERSISTENTLY RESTLESS TELICA VOLCANO, NICARAGUA.

ABSTRACT

Telica Volcano, Nicaragua, is a persistently restless volcano with daily seismicity rates that can vary by orders of magnitude. Low-frequency (LF) events dominate the seismic catalogue and peaks in seismicity rate show little correlation with eruptive episodes, presenting a challenge for seismic monitoring and eruption forecasting. A short period seismic station (TELN) has operated on Telica's summit since 1993, and in 2010 we completed the installation of a six-station broadband seismic and eleven-station continuous GPS network (TESAND network) to document in detail the seismic characteristics of a persistently restless volcano. Between installation of the first TESAND instrument in November 2009 and the most recent data recovery in May 2013, over 400,000 events were detected by the TESAND summit station (TBTN). During the three-and-a-half year TESAND deployment, we detected an average of approximately 300 events per day, but this rate has varied from a minimum of 5 events per day to a maximum of over 1400 events per day. We present spectral analyses and classification of ~200,000 events detected across the TESAND network between April 2010 and March 2013, and we present earthquake locations for a sub-set of events between July 2010 and February 2012.
In 2011 Telica erupted with a series of phreatic to phreatomagmatic vulcanian explosions. In late August 2010, six months before the 2011 eruption, we observed a swarm of LF and high-frequency (HF) events, which was immediately followed by a rapid decline in seismicity. We observed a brief increase in seismicity in October 2010, followed by a slow decline in event rates, which reached a minimum at the eruption onset. Additionally, we observed a change in the frequency characteristics of events during this precursory period; in particular, a loss of events with dominant energy below 3 Hz. We compare our seismic observations to other observations from the 2011 eruption, such as deformation, temperature, $SO_2$ rates and ash analysis and suggest sealing of the magmatic and/or hydrothermal system causes a transition from open-system degassing to closed-system degassing. During the three-and-a-half years of network operation we observe repeated periods broadly characterised by high and low seismicity rates. We suggest that these changes in seismicity rates represent repeated transitions between open-system degassing (high-seismicity) and closed-system degassing (low-seismicity) and that these observations have implications for seismic monitoring at persistently restless volcanoes.

### 3.1 INTRODUCTION

Increases in seismic activity are frequently observed before volcanic eruptions (McNutt, 1996, and references therein). The onset of low-frequency (LF) events, or the appearance of LF swarms, is often interpreted as a short-term indication of eruption, thus detection of LF seismicity is crucial to many aspects of volcano monitoring (Sparks, 2003). Precursory
sequences of events, including swarms of LF events, were identified at Redoubt Volcano, Alaska, before the main explosion phases of the 2009 eruption (Buurman et al., 2013; Ketner and Power, 2013). Swarms of volcano-tectonic (VT) earthquakes have also been observed prior to eruptions. For example, the 2006 eruption of Augustine Volcano, Alaska, was preceded by months of elevated rates of VTs (Jacobs and McNutt, 2010). Forecasting of eruptive activity based on increased rates of seismicity is complicated by volcanoes that exhibit seismic swarms without eruption, and by eruptions that have very short precursory seismic sequences. For example, the 2006 LF swarm at the Campi Flegrei Caldera, Italy (Saccorotti et al., 2007) did not culminate in an eruption, and the 2008 eruption of Okmok Volcano, Alaska was preceded by only five hours of precursory seismicity (Johnson et al., 2010). Monitoring changes in seismicity rates at volcanoes and understanding the physical changes behind such changes, remains challenging at volcanoes that do not follow typical patterns of seismic activity.

Persistently restless volcanoes (PRVs) (Stix, 2007) are characterised by highly variable rates of seismicity, persistent degassing and frequent explosions. PRVs do not experience clear ‘background’ or ‘unrest’ states, and instead experience phases of eruptive and non-eruptive behaviour that show little obvious correlation with geophysical measurements. For example, the 1999 sub-Plinian eruption of the persistently restless Shishaldin Volcano, Alaska was preceded by a short-lived seismic swarm, but much larger swarms occurred in other years with no subsequent eruptive activity (Petersen et al., 2006). Recognition of precursory seismic swarms is an important aspect of volcano monitoring, but the highly variable rates of seismicity observed at PRVs make forecasting eruptive activity based on changes in seismicity rates
challenging, highlighting the need for an improved understanding of the processes and patterns of seismicity occurring at PRVs. In this study we aim to characterise seismicity at a PRV during periods of eruptive and non-eruptive activity, and to investigate the transition between these two phases of activity.

Telica Volcano, Nicaragua is a PRV that exhibits unusual seismic activity before, during and after eruptions. Seismicity preceding the 1999 eruption of Telica followed an unusual precursory pattern, whereby seismicity declined in the months before the eruptive episode and before large explosions during the eruption (Chapter 2; Rodgers et al., 2013). In 2010 we installed a network of seismic and continuous GPS (cGPS) stations on Telica (Figure 3.1) to study its seismic and magmatic processes. In this study we analyse the seismicity at Telica over a three-year period from 2010 until 2013, including a period of phreatic eruptive activity in 2011. We compare our seismic observations of the 2011 eruption to deformation, temperature and SO$_2$ measurements, and to ash analysis from the 2011 eruption. We document and interpret changes in event rates and in event properties, including spectral content, over the three years of the network deployment, including changes in seismicity surrounding the 2011 eruption. In this study we find that rates of seismicity at Telica are highly variable, but that the pattern of seismicity surrounding the 2011 eruption shares certain similarities with the 1999 eruption, in that we observe a decline in seismicity in the months before the eruption. We also find that pertinent information can be extracted from the high rates of seismicity by considering the spectral content of events. We propose a model for the precursory seismicity patterns...
observed at Telica, where changes in seismicity are related to a transition from open-system to closed-system degassing.

Figure 3.1. Location of Telica Volcano and TESAND network stations: seismic stations (black inverted triangles), CGPS stations (white triangles) and pressure sensor (black circle). Inset map: Central America (right) and major volcanic centres of Nicaragua (left).

3.2 BACKGROUND
3.2.1 Telica Volcano, Nicaragua

Telica is a basaltic-andesitic volcano in the Maribios range of the Central American volcanic arc (Figure 3.1). Oblique subduction of the Cocos plate beneath the Caribbean plate at rates of ~80 mm/yr (DeMets et al., 2010), and the collision of the Cocos Ridge with the overriding Caribbean plate results in northwest fore-arc sliver transport at rates of ~10 mm/yr with respect to the Caribbean plate (LaFemina et al., 2009). The Telica volcanic complex is an east-west trending series of volcanic craters, with the oldest (La Joya) pit crater at the eastern end and the currently active crater at the western end (Roche et al., 2001).

Eruptive activity at Telica Volcano is characterised by small explosions every few years, and highly variable rates of volcanic seismicity are observed. Eruptions at Telica are typically low-explosivity phreatic to phreatomagmatic vulcanian eruptions (VEI 1-2), however large eruptions have occurred at Telica. The largest historical eruption occurred in 1529 (VEI 4) and is also the only recorded historical lava flow. Since improved recording of activity began in the 1970s, minor eruptive activity (VEI 1) has been documented approximately every 1-5 yrs, and VEI 2 eruptions have been documented in 1981-82, 1994, 1999 and 2011 (Siebert and Simkin, 2002; Geirsson et al., 2013). In 1993 the first permanent seismometer was installed 0.4 km from the active vent of Telica, and since then high-but-variable rates of seismicity have been observed. An average of ~4000 events per month has been recorded between 1997 and 2009 on this summit station. The rate varies from less than ten events for the entire month of June 1998, to almost 20,000 events for the month of May 2004 (Figure 3.2) (Tenorio, 1993-), but peaks in seismicity are generally not correlated with episodes of eruptive activity.
Figure 3.2. Monthly event rates from 1997 to 2009, reproduced from INETER monthly bulletins. For details on event detection parameters see Tenorio, 1993 onwards. Months for which there are no published data are indicated by asterisks under the time-axis. Months during which explosions/ash emissions were reported are indicated by arrows.

3.2.2 The TESAND experiment

Telica was chosen as a representative PRV for this study due to its relatively long catalogue of data and observations. In addition to the catalogue of short-period seismic data accumulated since 1993, geochemical and thermal observations have been made intermittently over the last two and a half decades (Smithsonian Institution, 1989 to present). In 2009-2010 the TElica Seismic ANd Deformation (TESAND) network was installed at Telica Volcano, Nicaragua. This network consists of six broadband seismometers (Guralp 6TD/6T), one pressure sensor (Chaparral 25V) and ten cGPS stations (Figure 3.1). The first broadband seismometer was
installed in November 2009 at station TBTN (Figures 3.1 and 3.3), the remaining five broadband seismic stations and the majority of the cGPS stations were installed in March 2010, and the pressure sensor (TBCF) was installed in June 2010 (Figure 3.3). The last data from stations TBTN and TBCF were retrieved in May 2013 and the last data from the remaining stations were retrieved in March 2013. At the time of writing the network is still operational and will be maintained for the foreseeable future.

**Figure 3.3.** Station operation time periods for all the TESAND network seismic stations are indicated by black horizontal bars. Data gaps of less than one hour are not displayed. Note that power problems occurred at TBCF from 2011 onwards and are indicated by frequent white gaps in the black bars.

The seismic network design was necessarily limited by the location of the pre-existing INETER concrete bunkers, which provide critical security for the instruments and peripherals. Two of the TESAND stations (TBTN and TBCA) were co-located with existing INETER short-period
seismic stations (TELN and TEL3) and all TESAND stations were located in purpose-built concrete bunkers. Station TBCF was built by the TESAND experiment to house a seismic and pressure sensor 0.2 km from the active vent. The location of the seismic stations gives good coverage for local events, with a maximum azimuthal gap of 130° around the vent and distances from the vent of between 0.2 km and 3.5 km (discounting station TBPV, which was only online for the first four months of the project).

### 3.2.3 Eruptive activity

#### 3.2.3.1 1999 eruptive episode

The 1999 eruptive episode began in May 1999 and continued for nine months, until February 2000. This VEI 2 eruptive episode consisted of discrete periods of explosions and ash emissions. The observations and reports of explosive activity from this eruption are qualitative and likely to be subjective. Periods with the most notable explosions occurred in August, October, November and December 1999, and explosions in August and December 1999 had eruption plumes up to 5 km elevation and deposited ash up to 45 km away from the vent (Tenorio, 1999; 2000). Analysis of the seismicity surrounding the 1999 eruption of Telica (Rodgers et al., 2013) shows a decrease in seismicity before the eruption: Three months before the onset of eruptive activity in May 1999 there was a significant decrease in LF seismicity, which was immediately followed by an HF swarm. The decrease in seismicity cannot be attributed to the onset of strong seismic tremor as RSAM remained low. This pattern of seismicity (i.e. a decrease in LF events followed by an HF swarm), was repeated in the period between the August and October 1999 explosions. LF seismicity remained low throughout November and December 1999 until
the explosions in December 1999. This pattern of seismicity was interpreted to be the result of sealing of gas pathways at Telica and may represent a transition from open-system to closed-system degassing. Pressure build-up during closed-system degassing could have been in part responsible for the 1999 explosions.

3.2.3.2 2011 eruptive episode

Telica erupted in 2011 with a three-month-long series of phreatic vulcanian explosions. The first ash emissions were noted on the 7th March 2011 and small explosions were reported in March and April 2011 (Geirsson et al., 2013). We note that the reports of explosive activity are subjective, and that descriptions of explosions are qualitative at best. On the 8th May 2011 three distinct explosions were observed throughout the day. These explosions on the 8th May 2011 are considered to be the start of a more energetic explosive period. Some of the most energetic explosions of the 2011 eruptive episode were observed on the 18th May and on the 21st May 2011, and had eruption plumes up to 2 km elevation. During the 21st May 2011 explosion, sustained ash emissions were observed for ~30 minutes. Eruptive activity then waned after the 24th May 2011 and the eruption ended by mid-June 2011.

SO₂ and temperature measurements were made during periods before and during the eruption. NOVAC (Network for Observation of Volcanic and Atmospheric Change (Galle et al., 2010)) instruments deployed between January and March 2010 measured an average SO₂ flow rate of 115 (+/- 100) tons/day, and during the eruptive episode in May-June 2011, an average of 140
A single mobile mini DOAS (Differential Optical Absorption Spectroscopy) measurement on the 16\textsuperscript{th} March 2011 indicated an SO\textsubscript{2} emission rate of 66 tons/day. Temperature measurements of the crater floor taken with a FLIR infrared camera indicate a stable temperature of \( \sim 200 \text{-} 300 \) °C in early 2010, which dropped to \( \sim 130 \) °C in February-March 2011 and then increased to 590 °C in June 2011 (Geirsson et al., 2013).

The lack of an observable deformation signal and the analysis of erupted material as non-juvenile and hydrothermal in origin suggest that the 2011 eruption was phreatic. The TESAND cGPS data demonstrate an entirely tectonic signal (Geirsson et al., 2013) and the lack of any deformation signal attributed to volcanic processes at Telica suggests that any intrusion of magma that may have occurred was either too small or too deep to be observed geodetically, or that any build-up of pressure as a result of sealing was also too small to be observed. Geodetic modelling shows that a closed vertical pipe of radius 100 m at 50-2000 m below the vent would produce detectable horizontal signals at excess pressures of 2 MPa (Geirsson et al., 2013). Ash analysis suggests that the erupted material was altered prior to eruption and the existence of accretionary lapilli in the deposits suggests a phreatic eruption.

3.2.3.3 Minor eruptive episodes

Minor ash explosions occurred at Telica every few years between the 1999 eruption and the 2011 eruption (see Appendix A – Table A1). As discussed before, descriptions of explosions at Telica are highly subjective and the terms are qualitative at best. In January 2001 ash plumes
were observed and deposited ash within a 500m radius of the vent (Smithsonian Institution, 2009a). Explosions and ash clouds were observed in July, September, October and December of 2001 (Smithsonian Institution, 2009a). In March 2004 an explosion was observed visually and in June 2004 an explosion was detected seismically (Smithsonian Institution, 2009b). Ash explosions were then observed in November of 2004 and in January 2005 (Smithsonian Institution, 2009b). In August 2006 ash explosions were observed and ash fall was reported in local communities (Smithsonian Institution, 2009c). These explosions opened a new vent in the west portion of the crater (Smithsonian Institution, 2009c). Explosions were detected seismically in December 2006 and in January 2007 phreatic explosions were observed (Smithsonian Institution, 2009c). Explosions were observed in February, June, October and November of 2007 (Smithsonian Institution, 2009c). Ash emissions were reported in July of 2008 and this was the last reported eruptive activity until May 2011 (Smithsonian Institution, 2009c).

3.2.4 Crater observations: 2009-2013

The active vent at Telica is within a large pit crater located just below the summit of Telica. The crater is ~400 m wide and ~200 m deep and the active vent is in the deepest of a series of three nested craters (Figure 3.4). Between November 2009 and March 2013 a total of 12 maintenance visits were made to the TESAND stations. During all but one of these visits (January 2013) photographs were taken of the crater floor (Appendix A - Figure A1). These photos show that the morphology of the crater floor changes over time and that incandescence was visible between 2009 and 2013 (incandescence was visible during 7 of the 11 field visits).
The absence of incandescence during some visits may represent a genuine cooling of the crater floor rocks, or may represent the time of day, sunlight conditions, or gas conditions within the crater when the photographs were taken. Incandescence was observed during visits in November 2009, March 2010, August 2011, November 2011, July 2012, September 2012, January 2013 and March 2013. Persistent fumaroles are present at the base of the second crater and along the walls of the main crater. On the 13th and the 14th January 2013 small ash plumes were observed, but these small, diffuse plumes barely rose above the crater rim.

The incandescence observed in August 2011 was by far the most areally extensive, and was easily observed in the daytime during bright sunlight conditions. From measurements taken with a laser range instrument we estimate the diameter of the inner crater to be ~30 m, and the diameter of the daytime incandescent circle observed in August 2011 to be ~7 m. Repeated observations of the incandescence from the 9th – 16th August 2011 (Figure 3.5) indicate that the morphology of the incandescent area changes over this short time scale. During night time observations of the incandescence in August 2011, small showers of incandescent material were ejected from some of the brighter areas of incandescence. Unfortunately these ‘micro-Strombolian’ events were too small to be captured on camera.
Figure 3.4. Annotated photograph of Telica’s crater, taken from the main crater rim (i.e. first crater). The second crater, the inner crater and the incandescent circle are marked with arrows. Vertical distances (A-E) and horizontal distance (F) are from the crater rim where the photograph was taken. A: 193m B: 189m C: 155m D: 144m E: 111m F: 343m.
Figure 3.5. Series of photographs showing changes to the incandescent circle in the inner crater at Telica. Photographs were taken from the same spot on the 9th August 2011, 11th August 2011 and the 16th August 2011.

3.3 SEISMIC DATA ANALYSIS

3.3.1 Seismic data

The continuous seismic data analysed in this study come from a network of between four and six broadband seismometers (Figure 3.1). A sampling rate of 100 Hz was used for station TBCF (the co-located seismic and infrasound station), and a sampling rate of 50 Hz was used at all other seismic stations. Seismic data were stored locally on the instruments and downloaded every three months during maintenance visits. TBTN was chosen as the primary station for single-station analyses due to its proximity to the vent, minimal data gaps and continuity with the short-period INETER station TELN. Instrument response information for all stations can be found in Appendix B.
3.3.2 Data analysis overview

Given the high and variable rates of seismicity at PRVs, analysing parameters in addition to event rates, such as spectral content, event amplitudes, event classification and earthquake locations, is critical to assess whether or not seismic parameters vary systematically with changes in surface activity. Total daily event rates were calculated from a single station (TBTN) close to the vent, to give an overview of the variation in seismicity throughout the study period. Over 400,000 events were detected from this single-station analysis. An event detection algorithm run on data from the full TESAND network (as described below in section 3.3.3) was used to create a smaller catalogue of ~200,000 events that were used for detailed analysis of event properties such as spectral content and amplitudes. We took two approaches to analysing the spectral content of events. First, we looked at the dominant spectral peak of each event, and secondly we analysed the ratio of high- to low-frequency energy in each event. Plotting the dominant frequency of each event is a simple yet effective way of illustrating spectral variations over time for large earthquake catalogues. Comparison of our dominant frequency plots to ESAM (Earthquake Spectral Amplitude Measurements) (Moran et al., 2008) calculated for stations TBTN and TBMR demonstrates that these dominant frequency plots effectively convey the overall frequency content of the data over the entire study period (see Appendix C for further details). The second spectral analysis we performed involved plotting the frequency ratio between high to low frequency bands (Buurman and West, 2010; Thelen et al., 2010). This method allowed us to assess more subtle variations in spectral content. Events classifications were then assigned to each event in the sub-catalogue based on these frequency ratios. Finally, to assess the location and to identify any spatio-temporal migration of
earthquake depths, a sub-set of events from a 20-month period surrounding the eruption was chosen for an initial location analysis.

### 3.3.3 Event detection and RSAM

We used Antelope Environmental Data Collection Software (http://www.brtt.com) to create a catalogue of event detections and associated waveforms from the continuous data from our entire network. The Antelope event detection method uses a multiple station, short-term average/long-term average (STA/LTA) approach to detect candidate seismic events. If detections occur on more than a given number of stations at the same time (we used a three station minimum and a 1.5 second time window for associated detections) a grid search is performed to attempt to define an origin point for the earthquake, and only if an origin point can be found within the specified grid is the event added to the catalogue. This multi-station STA/LTA approach minimises the chance of noise on a single station being detected as an event, and the grid search approach minimises regional earthquake inclusion in the catalogue, and also minimises the chance of noisy data with multiple triggers on multiple stations from being catalogued as an event. Due to the necessary prerequisite that the event must be detected at multiple stations, this detection method will miss small events that would only be detected at the closest stations (e.g., station TBTN). As with any detection method, event rates will be affected by station outages.
As small events that are only visible at the closest stations may be missing from the Antelope catalogue, we also compiled a single-station detection catalogue from station TBTN, which is 0.4 km from the active vent (Figure 3.1), and which has a slightly longer continuous record of data than the other TESAND stations. The vertical component of the continuous seismic data was high-pass filtered at 0.5 Hz to remove microseism noise, and an STA/LTA event detection algorithm (AECAP, Powell, 2004) was used to detect events (Table 3.1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AECAP</th>
<th>ANTELOPE (HF)</th>
<th>ANTELOPE (LF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STA window (seconds)</td>
<td>1</td>
<td>1.4</td>
<td>2.3</td>
</tr>
<tr>
<td>LTA window (seconds)</td>
<td>60</td>
<td>7</td>
<td>11.5</td>
</tr>
<tr>
<td>Threshold on</td>
<td>8</td>
<td>3.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Threshold off</td>
<td>3</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Filter (Hz)</td>
<td>0.5 - 20</td>
<td>3 - 18</td>
<td>0.5 – 10</td>
</tr>
</tbody>
</table>

RSAM (Real-time Seismic Amplitude Measurement) (Endo and Murray, 1991) was calculated from the vertical component of station TBTN using one–hour long windows. The continuous data were first filtered between 0.5 – 20 Hz, to remove microseism noise below 0.5 Hz and to remove wind noise above 20 Hz. However, wind noise that occurs below 20 Hz cannot be distinguished in the RSAM calculation from the volcanic signal of interest. Due to the susceptibility of RSAM at Telica to noise, the trends in the RSAM data will not be discussed in detail and are provided here primarily to assess the possible effect of volcanic tremor on the rate of detected events.
3.3.4 Spectral analysis and amplitude

3.3.4.1 Dominant frequency and amplitude

The dominant frequency of every event in the Antelope catalogue was calculated based on the fast Fourier transform (FFT) of a 12 second window around the largest peak in the waveform (4 seconds before, 8 seconds after). The largest peak in the power spectral density between 1 and 15 Hz was chosen as the dominant frequency for the event (Figure 3.6). The amplitude of each event was calculated by taking half the maximum peak-to-peak amplitude of each waveform, after the mean had been subtracted (Figure 3.6a).

3.3.4.2 Spectral ratios

Average spectral amplitudes for high and low frequency bands were used to determine spectral ratios for every event in the Antelope catalogue (Figure 3.6b) (Buurman and West, 2010). The dominant frequencies of events at all stations were visually inspected (See Appendix A – Figure A4, for dominant frequency plots from all stations) and based on the similarity of the dominant frequencies at five of the six stations, frequency bands of 1-6 Hz (low) and 6-11 Hz (high) were chosen. A 6 Hz threshold between the low and high frequency bands was chosen as many events had dominant spectral energy around 4 to 5 Hz, and choosing the more conventional 5 Hz threshold (Lahr et al., 1994) would have caused events with energy at ~ 5 Hz to be too close to the threshold, potentially allowing small variations in the frequency of the events to have a significant effect on the ratio. For every event the log base 2 of the ratio of high-frequency energy to low-frequency energy was calculated (Buurman and West, 2010; Thelen et al., 2010). This method was chosen to give events with dominantly low-frequency energy a negative value,
events with dominantly high-frequency energy a positive number, and events with equal amounts of low and high energy a value of zero. By choosing log base 2, the negative and positive ratios then give an equal indication of the relative amounts of high to low energy, with a value of 1 indicating there is twice as much high-frequency energy as low-frequency energy, and a value of -1 indicating there is twice as much low-frequency energy as high-frequency energy.

Figure 3.6. a) Waveform (top), spectrogram (bottom), and b) periodogram (inset) of example low-frequency event from the 1st April 2010 from station TBTN. Spectrogram produced using a window size of 2s, overlap of 1s and FFT size of 256.
### 3.3.5 Classification

Consistent event classification is an important part of quantifying changes in seismicity, and relating seismicity characteristics to source processes (Minakami, 1974; Lahr et al., 1994; McNutt, 1996). In volcano observatories, events are classified manually by a seismic analyst. While there are advantages to this approach in that every event is assessed by an analyst such that noise is unlikely to be catalogued as an event, there can be inconsistencies in event classification between different analysts. Also, at volcanoes such as Telica that have hundreds of events per day, it is impractical to analyse this amount of data by hand. Automated classification of events provides consistency across long periods of data and provides a systematic and automated approach for efficiently analysing many thousands of events.

In this study classifications were assigned to detected seismic events based on their spectral ratios: if an event had 1.5 times the amount of low-frequency energy to high-frequency energy it was classified as a low-frequency event (Figure 3.7a). If an event had 1.5 times the amount of high-frequency energy to low-frequency energy it was classified as a high-frequency event (Figure 3.7b). Events in between these two boundaries (i.e., events with similar ratios of low to high frequency events) were classified as mixed-frequency (MF) events (Figure 3.7c). This three-tier classification scheme was chosen to ensure that events classified as LF or HF are dominantly low or high frequency, respectively, and to avoid potential situations where two very similar events with energy at approximately 6 Hz could be classified differently based on slight changes in spectral content. An event classed as MF could either be an event with narrow band energy...
Figure 3.7. Periodograms of three selected events, a) Low-frequency event, b) High-frequency event, c) Mixed-frequency event. Relative amplitude ratios are indicated by colours: Blue indicates energy below 6 Hz; red indicates energy above 6 Hz.
at approximately 6 Hz, or equal energy across a wide spectrum; our MF class does not distinguish between the two.

Classification across the network occurred through a two stage process. Rather than determining the average spectral ratio across the network, which could potentially be skewed if there was noise on one or more stations, we employed a system in which events were classified at each station and then those classifications were compared across three stations. Stations TBTN, TBMR and TBHY were chosen for the classification process as these have the most complete continuous waveform data, and to the best of our knowledge data is not clipped at these stations (see Appendix D). TBHS was considered as a potential station for this process, but was discarded due to an anomalous absence of low-frequencies in the dominant-frequency plot (see Appendix A – Figure A4a), perhaps indicating a site effect at this station or a path effect in the azimuth to this station (McNutt, 2005, and references therein). Stations TBCF and TBCA were discarded due to data gaps. To minimise noise or path effects influencing the classification, for an event to be given a final class it had to have the same classification at two or more stations. We chose to use two stations for this classification, rather than all three stations, so that any events that were noisy at one station were not unnecessarily removed from the catalogue. However, events with three different classifications were not included, as it is likely that these events were affected by noise or path effects.
As the dominant frequencies of many events (Appendix A – Figure A4) are clustered in the 3 to 5 Hz range, we also chose to perform an additional sub-classification of low-frequency events with spectral energy below 3 Hz. Selection of these events was based on the dominance of spectral amplitude below 3 Hz at station TBTN only.

3.3.6 Locations

To determine whether or not the location of seismic events varied surrounding the 2011 eruption we located a sub-set of earthquakes from the Antelope catalogue for the period 1st July 2010 to the 29th February 2012. Of the 200,000 earthquakes in the catalogue we selected the 100 largest-amplitude earthquakes (based on amplitude at TBTN) in this 20-month period. As events in the catalogue are typically small and emergent, selection of the 100 largest amplitude events gave us the best chance of obtaining well-constrained locations.

For events in our sub-sampled catalogue we picked P-wave arrivals, and where possible S-wave arrivals by hand, using two iterations of picks, and events were located using the program HYPOCENTER (Lienert and Havskov, 1995). We used the same 1-D velocity model as used by the Alaska Volcano Observatory for Shishaldin, Alaska (Dixon et al., 2006; McNutt and Jacob, 1986). Shishaldin shares many similarities to Telica in terms of composition (they are both basaltic-andesite volcanoes) and eruptive style (they both have frequent small eruptions).
3.4 RESULTS

3.4.1 Single-station total event counts and RSAM

A histogram of total daily seismic event rates is plotted alongside RSAM for station TBTN to see variations in daily event rates (Figure 3.8) (For cumulative event rates see Appendix A, Figure A2). In total over 416,000 events were detected by our single-station STA/LTA method. Over the entire study period from the 26th November 2009 to the 15th May 2013 there is an average seismicity rate of 329 events per day. The daily event rate shows considerable variation, ranging from a minimum of 5 events on the 17th March 2011, to 1419 events on the 21st March 2013.

Figure 3.8. Total daily seismic event counts (black bars) and RSAM (black circles) from November 2009 until May 2013 from station TBTN. The 2011 eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey. The January 2013 explosion is marked by a thin grey vertical bar.
At the beginning of the study period the event rate is fairly constant at approximately 500 events per day between November 2009 and the end of August 2010. There is a short-lived peak in event rates in August 2010, with a high point of 994 events on the 25th August 2010, after which event rates start to decline in September 2010, reaching a low of 72 events on the 28th September 2010. The event rate then increases again, reaching a high of 438 events on the 21st October 2010, before decreasing gradually, reaching a minimum of 5 events on the 17th March 2011, ten days after the start of the 2011 eruptive episode. RSAM throughout 2010 and until March 2011 remains constant: Aside from an approximately ten-day increase in RSAM in September 2010, there is very little change in RSAM during both the sudden drop in seismicity in September 2010 and the gradual drop in seismicity between October 2010 and March 2013. This suggests that the drop in event rate cannot be attributed to tremor or other non-detected signals saturating the STA/LTA detection algorithm, and therefore that we can have confidence that the decrease in event rate during this time is a real reduction in events. An example waveform from February 2011 (Appendix D – Figure D2) suggests that there is no significant background noise (when compared to other time periods) that would indicate this event rate drop is due to saturation of the detection algorithm. However, the fact that RSAM remains constant during these two periods of decreasing seismicity, rather than also decreasing, suggests that the RSAM signal during the high-seismicity period (November 2009 to August 2010) is not dominated by the seismic signal.

Approximately two weeks after the onset of the eruption in March 2011, the event rate starts to increase again. A sudden increase occurs during the onset of the more energetic phase of the
eruption on the 8th May 2011. The event rate reaches a high of 720 events on the 12th June 2011, shortly before the end of the eruptive episode, and then decreases throughout July and August 2011. RSAM starts to decrease in March 2011, just before the onset of eruptive activity and then increases rapidly in May 2011, (the explosions in May 2011 represent the more energetic phase of the eruption, see section 3.2.3.2).

After reaching a post-eruption minimum of 104 events on the 5th September 2011 there is then a series of three swarms lasting one to two months each. These swarms occur in September 2011, November 2011 and February 2012 and reach maxima of 900-1400 events per day with minima of 100-300 events per day in between the swarms. Although the data are noisy, peaks in the RSAM appear to correspond to increases in event rates during these swarms. After the third swarm in the series, event rates start to decline. This decline continues over the next eight months, from ~250 events per day in April 2012 to ~10 events per day in December 2012. RSAM also follows this overall declining trend but remains higher than the pre-eruptive RSAM level throughout this time, indicating larger amplitude post-eruption events. In January 2013 event rates start to increase again, and after a brief drop in event rates in February 2013, a final swarm of events occurs from March - May 2013. The maximum event rate of the entire study period is observed during this swarm, reaching 1419 events on the 17th March 2013. Again there is a corresponding peak in RSAM during this final swarm. The event rate decreases after the peak in March 2013 and continues to decrease until the end of the study period on the 15th May 2013. There is no annual or seasonal component component to the seismicity or RSAM rates (see Appendix A: Figure A3).


3.4.2 Spectral analysis and amplitude

Spectral analysis and amplitude information for stations TBTN and TBMR are shown in Figures 3.9 and 3.10, respectively (See Appendix A - Figures A4, A5 and A6 for other stations). Data for this analysis is from the Antelope catalogue, which runs from the 1st April 2010 until the 18th March 2013, and contains almost 218,000 events. As discussed in section 3.3.1, we chose TBTN as our main station, and of the remaining sites we chose to display data from TBMR. TBMR is on the other side of the vent from TBTN, such that any path effects generated in the conduit area would hopefully be evident in our analysis. Station TBHS is also opposite the vent from TBTN, however, the dominant frequencies of events at TBHS (Appendix A – Figure A4) indicate events mainly have energy between 5-8 Hz, which is anomalous when compared to the dominant frequencies at the other 5 stations. Additionally, TBMR has the best station coverage of all the other stations, with almost no data gaps since its installation (Figure 3.3).

Stations TBTN and TBMR show very similar temporal variations in spectral content and amplitudes during the study period. Between April and August 2010, low frequency energy dominates the catalogue. The dominant frequency plots (Figures 3.9a and 3.10a) indicate that most events have frequencies below 6 Hz and the band-ratio plots (Figure 3.9b and 3.10b) show that events have ratios mainly below -1 (i.e., events with more than twice the amount of low-frequency energy to high-frequency energy).

At the beginning of September 2010 there is a marked change in spectral content. Events with frequencies in the 6-15 Hz range appear (Figure 3.9a and 3.10a) and the band-ratios during this
period show a range of ratios from -4 to 2 (Figures 3.9b and 3.10b), suggesting events are occurring across a very broad range of frequencies. Co-incident with this pulse of events that has a broad range of frequencies, the amplitudes of events decreases (Figures 3.9c and 3.10c). This broadband pulse is followed by a cessation of events with frequencies in the 1-3 Hz range at TBTN and in the 1-2 Hz range at TBMR and can be seen in the band-ratios as a jump in the lower limits from ~3 to ~2. In the six-month period before the onset of the eruption, from October 2010 to March 2011, there is a narrowing in the range of band-ratios and events with dominant frequencies in the 6-15 Hz range disappear. The amplitude of events between October 2010 and March 2011 show a considerable amount of scatter, but there is an overall increase in the amplitude of the events until the end of January 2011.

There is no obvious change in any of the event properties we measured at the onset of the eruption in March 2011. However, a change is observed after the onset of the more energetic phase of the eruption in May 2011 (Figure 3.9 and 3.10). At the onset of the energetic phase, the band-ratios indicate an increase in the low-frequency content of the events and the amplitudes increase. Towards the end of the eruptive episode, high-frequency content is observed as a peak in the band-ratios; this is also observed as a reappearance of events with dominant frequency in the 6-15 Hz range. At station TBTN, in the three month period after the eruption, dominant frequencies in the 6 – 9 Hz range form bands that slide upwards in frequency content over time. This is the only time these sliding bands are observed in the study period.
Figure 3.9. Multi-parameter information for each event at station TBTN from April 2010 until March 2013. a) Dominant frequency, b) frequency band-ratio, c) amplitude. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey.
Figure 3.10. Multi-parameter information for each event at station TBMR from April 2010 until March 2013. a) Dominant frequency, b) frequency band-ratio, c) amplitude. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey.
The three swarms in September 2011, November 2011 and February 2012 that are seen as large increases in event rates (Figure 3.8) can also be seen in the amplitude and the band-ratio plots (Figures 3.9b, c and 3.10b, c). Amplitudes increase during these swarms and band-ratios show broadband pulses of events with ratios between -4 and 1.5. These swarms are not seen clearly in the dominant frequency data (Figures 3.9a and 3.10a); they appear only as perturbations to the dominant bands of frequencies. After the swarms, from April 2012 onwards, there is a narrowing of the band-ratios into the HF range, and a decrease in amplitudes (Figure 3.9 and 3.10). The Antelope catalogue ends on the 18th March, in the middle of the final swarm of events (as seen on the single-station analysis (Figure 3.8)), but it appears that a broadband pulse of band-ratios started during this swarm (Figure 3.9b and 3.10b).

### 3.4.3 Event rates of classified events

Histograms of events classified by frequency content reveal interesting changes in the pattern of seismicity at Telica (Figure 3.11) that are not readily evident from analysis of total seismicity (Figure 3.8). LF events dominate the catalogue, with an average of 103 events per day, compared to 73 MF and 18 HF events per day (Figure 3.11). In April 2010, at the start of the catalogue, LF event rates are ~200 events per day and there are almost no HF or MF events. The drop in LF event rates between mid-April and June 2010 corresponds to a period when station TBHS was not operational and TBCF had not yet been installed, leaving only three proximal stations in the network (TBTN, TBMR and TBHY). As the Antelope detection parameters require an event to be detected on at least three stations, we believe this drop in April 2010 and subsequent increase in June 2010 of the LF event rate to be a consequence of the network
configuration. This supposition is further supported by the consistency of event rate from the single-station detections at TBTN during this time (Figure 3.8).

In late August 2010 there is a spike in LF events (Figure 3.11), with 687 events on the 25th August 2010, followed seven days later by a peak in both HF events (86 events) and MF events (374 events) on the 1st September 2010. During September 2010 there is a rapid decrease in event rates of all classes, reaching a minimum of 32 LF events, zero HF and five MF events on the 27th September 2010. Event rates for all three classes increase briefly in October 2010, before starting a gradual decline that continues until March 2011. The eruptive episode starts on the 7th March 2011 and the event rate minimum occurs nine days later, with two LF; zero HF and one MF events on the 16th March. LF event rates do not start to increase significantly until after the onset of the more energetic phase of the eruption in May 2011, going from approximately 50 events per day in late April 2011 to a peak of 416 on the 10th June 2011. There is a brief increase in HF rates in April 2011, halfway through the first stage of the eruption, but rates do not increase significantly until the end of the eruptive period, going from ten events per day at the end of May 2011 to a peak of 143 events on the 27th June 2011. Both LF and HF events decrease during July and August 2011, but MF events remain between ~ 100-200 events per day until May 2012.
Figure 3.11. Daily event rates for the three classifications used in this study. a) Station operation period for TESAND network (same as Figure 3.3), b) LF events, c) HF events, d) MF events. See text for detailed explanation of this classification scheme. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey.
The swarms in September 2011, November 2011 and February 2012 are clearly seen in the LF event rate. The maximum LF rate of the study period occurs during the November 2011 swarm, reaching 760 events on the 9th November 2011. Peak HF rates during the November swarm occur at the same time as the LF events, with 98 events occurring on the 10th November 2011, but peak rates for the MF events do not occur until the 27th November 2011, with a peak rate of 320 events. After the February 2012 swarm the LF events almost cease, with an average of only 17 events per day between the 1st April 2012 and the 28th February 2013. A final swarm of events began at the end of the study period (as seen from the single-station detections (Figure 3.8)), but data from the full network were not available after the 18th March 2013. Reduction in the HF and MF event rate occurs simultaneously in June 2012 and reaches a minimum at the end of 2012 (Figure 3.11).

The variation in the spectral analysis at TBTN (Figure 3.9) for events with frequencies below 3 Hz can be best observed by plotting a histogram of only events with dominant spectral amplitudes below 3 Hz (Figure 3.12). Event rates are similar to those with the general LF classification, but there are differences. The first noticeable difference is that in late August 2010 there is a significant spike in the <3 Hz events, with a maximum of 310 events on the 25th
Figure 3.12. Daily event rates for events with frequency content below 3 Hz at station TBTN. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey.

August 2010. This spike occurs just before the sharp decrease in overall event rates (Figure 3.8) in September 2010. The second noticeable difference is that the <3 Hz events are almost non-existent between October 2010 and April 2011 (Figure 3.12), with an average of 2.6 events per day between the 1st October and the 1st April 2010, compared to the average of 14 events per day for the entire catalogue. The <3 Hz events increase to a brief peak at the onset of the energetic phase of the eruption in May 2011, with 59 events on the 14\textsuperscript{th} May 2011, but quickly drop to 3 events per day by the 23\textsuperscript{rd} May 2011. The LF event rate remains high during this time. The three swarms in September 2011, November 2011 and February 2012 are clearly seen by rapid increases in the <3 Hz events from less than ten events per day to peaks of 115 (15\textsuperscript{th} September 2011), 65 (27\textsuperscript{th} November 2011), and 170 (20\textsuperscript{th} February 2013) events per day. By the end of March 2012 the <3 Hz events return to very low levels, with an average of 2.1 events
per day between the 1\textsuperscript{st} April 2012 and the 28\textsuperscript{th} February 2013. In March 2013 a final swarm occurs with a peak of 230 events on the 12\textsuperscript{th} March 2012. The catalogue then ends on the 18\textsuperscript{th} March 2013.

\subsection{3.4.4 Locations}

Due to the emergent onsets of the earthquakes, low amplitudes, shallow locations, and velocity model uncertainties, very few high-quality locations were obtained. Of the 2,000 events that were picked and located only 207 met our selection criteria of azimuthal gap <180°, RMS <0.2 s, horizontal and vertical uncertainties (as output by HYPOCENTER) <5 km, number of stations > 3.

The event locations cluster beneath the vent, with the majority of the events located within a 500 m radius of the vent (Figure 3.13). All events are shallow and no events occur below 2 km depth below datum, where the datum is taken as 1 km above sea level and is approximately the summit elevation of Telica. Classifications from section 3.3.5 were used for these events, and events that had been discarded from that classification system were given the classification from station TBTN. There appears to be little difference in the locations of LF and MF events. There are only 10 located HF events, which cluster to the south of the vent, and all but one of the HF events are shallower than 1 km below datum.
Figure 3.13. Locations and depth cross-sections of the 207 well located events from the 1st July 2010 until the 29th February 2012. Depths shown are below a datum that is taken as the summit elevation of Telica (~ 1km). TESAND seismic stations are shown by inverted black triangles, LF events shown by black stars, HF events by white diamonds and MF events by grey squares. The active vent of Telica is shown by a grey cross. Inset (top right) shows depth-time plot of all events.
3.4.5 Focus on the 2011 eruption period

The most recent eruptive episode began on the 7th March 2011 with minor ash emissions. The main phase of the 2011 eruption began on the 8th May 2011, and ended in mid-June 2011. There was an overall decrease in seismicity from October 2010 onwards and there was almost no precursory seismicity in the month before the eruption. During the one month period before the eruption there was an average of 25 LF, 1.2 HF and 13 MF events per day (Figure 3.14); these rates are all significantly lower than the averages for the entire study period (103 LFs, 18 HFs and 73 MFs per day). Dominant frequencies are in the 4-5 Hz range and band ratios vary between -2 and zero, indicating dominantly low frequency energies. Amplitudes of the events occurring before the eruption show considerable scatter.

Event rates during the first phase of the eruption indicate two minor swarms, the first at the end of March and beginning of April 2011 with a peak of 174 total events, and the second at the end of April with a peak of 346 total events (Figure 3.14). The first noticeable change in event rates during the eruptive episode occurs on the 26-27th March 2011, 20 days after the onset of the eruption. LF events rates increase from 3 events on the 25th March 2011 to 32 events on the 27th March 2011 reaching a peak of 55 events on the 2nd April 2011. The <3 Hz class represents a subset of the LF event class and these events increase from 3 events on the 26th March 2011 to 15 events on the 27th March 2011, reaching a peak of 22 events on the 2nd April 2011. HF events increase from 1 event on the 25th March 2011 to 8 events on the 26th March 2011, reaching a peak of 10 events on the 2nd April 2011. MF events increase from 12 events on the 26th March 2011 to 31 on the 27th March 2011, also reaching their peak of 109 events on
Figure 3.14. Multi-parameter information for the 2011 eruptive episode. Data is presented for the period 1\textsuperscript{st} February 2011 until the 30\textsuperscript{th} June 2011. LF, HF and MF events are from full network classifications. The < 3 Hz events, the dominant frequency, band-ratio and amplitude plots are from station TBTN. Earthquake depths are from the full network and LF events shown by black stars, HF events by white diamonds and MF events by grey squares. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey.
the 2\textsuperscript{nd} April 2011. Event rates then rapidly decrease, reaching a minimum by the end of the first week of April 2011. In late April 2011, there is another brief peak in event rates, this time more noticeable in the MF class. LF events reach a peak of 90 events on the 21\textsuperscript{st} April 2011 (and of these LF events, events with dominant energy $<$3 Hz reach a peak of 32 events on the 27\textsuperscript{th} April 2011), HF events reach a peak of 36 events on the 28\textsuperscript{th} April 2011 and MF events reach a peak of 254 events on the same day. Amplitudes of events in these two small swarms are low and there is an increase in the frequency content of the events. Earthquake depths of the only two earthquakes located during the second swarm are shallower than those located in the first swarm; however, there are too few located events during this period to assess whether this difference is real. After this second swarm event rates then reach another minimum (at the beginning of May 2011) before starting to increase again.

The main phase of the eruption is considered to have started on the 8\textsuperscript{th} May 2011, when the larger explosions were observed, after which we observe an increase in events rates across all classes. There is a very noticeable peak in events with $<$3 Hz energy on the 14\textsuperscript{th} May 2011 (Figure 3.14), reaching a maximum for the eruption of 59 events. This peak rapidly dies away and by the 27\textsuperscript{th} May 2011 only 2 events with $<$3 Hz energy occur. A peak in event rates is also noticeable in the HF and MF classes, with events reaching a maximum of 72 HF and 572 MF events on the 14\textsuperscript{th} May 2011, before decreasing to $\sim$10 HF and $\sim$130 MF events per day by the 21\textsuperscript{st} May 2011. However, after a brief peak in LF rates to 145 events on the 14\textsuperscript{th} May 2011, the LFs then start to increase dramatically, reaching a maximum of 416 events on the 10\textsuperscript{th} June 2011. The amplitude of events also starts to increase dramatically during this period, and there
is also a loss of events with higher-frequency content, combined with enrichment in the lower-frequency content, as seen by a drop in the upper and lower bounds of the band-ratios. HF events do not start to increase until the 31\textsuperscript{st} May 2011, and do not reach their maximum of 143 events until the 27\textsuperscript{th} June 2011, after the eruptive episode is considered to have finished. MF events remain steady at approximately 150 events per day for the remainder of the eruptive period. Earthquake depths during the second half of the main eruption phase do not show any clear spatial migration. At the end of the eruptive period, event rates for both LF and HF events are high, event amplitudes are high and there is a broad range of frequency content of events.

3.4.6 Summary of observations

- Event rates for LF, HF, and MF events are highly variable and LF events dominate the catalogue.
- Six months before the onset of the 2011 eruption, there is a swarm of LF events, closely followed by a swarm of HF events (Figure 3.15).
- After the swarms there is a rapid decline in seismicity, which reached a minimum just after the onset of the eruption in March 2011. There is a decrease in the number of events with low-frequency energy during this six-month period.
- Seismicity does not increase until after the onset of the energetic phase of the eruption in May 2011. Post-eruption seismicity is high, particularly for HF events.
- Locations of the largest-amplitude earthquakes from a 20-month period surrounding the eruption demonstrate that events are shallow (<2 km) and are clustered around the
vent. They show neither spatiotemporal migration of events nor clustering of events with the same classification (i.e., LF, HF and MF).

![Figure 3.15. Summary of key observations. The 2011 eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey. The January 2013 explosion is marked by a thin grey vertical bar.](image)

### 3.5. DISCUSSION

#### 3.5.1 Potential event classification and location biases

Recognition of LF and volcano-tectonic (VT) swarms has proved invaluable in forecasting many volcanic eruptions (Stephens et al., 1994; Harlow et al., 1996; Varley et al., 2010); however, correct identification of event types is crucial to this process. Automated event classification allows for efficient classification of large data catalogues and removes analyst inconsistencies, but it also has the potential to classify noise as a volcanic event provided the event matches the automated classification parameters. There have been many attempts to develop a consistent and reliable automatic classification process. Supervised neural network approaches have been
used to automate the event classification process at volcanoes such as Mt Vesuvius, Italy (Scarpetta et al., 2005), Soufriere Hills Volcano, Montserrat (Langer et al., 2003) and Villarica, Chile (Curilem et al., 2009). This approach depends on a pre-processing stage using a training data set of analyst-derived classifications, and has been shown to be highly successful when tested against the analyst classification (Langer et al., 2006). This approach may work well at volcanoes for which there are well-defined classifications and catalogues to draw from, but may be too time-intensive for use at minimally-monitored volcanoes, or in a rapidly escalating situation at a volcano with no historical catalogue. Automatic identification and classification using wavelet transforms and Hidden Markov Models has been used to successfully classify events at Merapi Volcano, Indonesia (Alasonati et al., 2006). This approach is excellent for identifying and then classifying volcanic signals in noisy seismic data (Beyreuther et al., 2008), but again, this technique, while highly successful in identifying and classifying events, requires a training process and only works for known event types, i.e. it cannot recognise a new type. Much of the crucial information for classifying an event lies in the frequency domain and simpler methods based on spectral content alone have been used to successfully classify events. The frequency ratio approach has been used to classify events at Augustine Volcano, Alaska (Buurman and West, 2010) and at Bezymianny, Russia, (Thelen et al., 2010). The advantage of this approach over more complex analysis, such as neural networks or Hidden Markov Models, lies in the ability to rapidly implement this technique on large data sets without any training period. In this study we used a frequency ratio classification approach due to the large data catalogue (>200,000 events) and the lack of any prior analyst catalogue.
While LF seismicity dominates the Telica catalogue, the frequency content of events demonstrates a wide range of event types and source processes. The MF classification may contain events that are predominantly LF events, but with some HF contamination, or vice versa. VT events contain a broadband onset, followed by a lower-frequency coda (Lahr et al., 1994) and in our classification system some may have been classified as MF events. The motivation for including a third MF class rather than the usual two-tier system was to improve our confidence in the LF and the HF classes. Source processes at Telica may be represented by a continuum of frequencies and by introducing the MF class we are able to better split the catalogue into LF and HF events. However, because the MF class may incorporate VTs as well as noisy LFs, we do not attempt to interpret the temporal evolution of MF events at Telica with respect to eruptive activity. A more in-depth analysis of the MF class of events will be the subject of further work.

For event locations we selected the 100 largest-amplitude events at station TBTN, and this approach may have introduced a bias into the locations. We are choosing to only locate the largest events and thereby ignoring the locations of smaller events; however, given the small and emergent nature of the events it is unlikely we would have been able to locate any but the largest amplitude events anyway. Another concern with the selection of the 100 largest events at station TBTN is that we are introducing a depth bias (i.e., the largest amplitude events might be just the shallowest events and deeper events of the same size are being ignored). There is also likely to be a location bias given the network configuration. We cannot locate anything outside of our network, in particular as we have no distal station to the northeast, we are
limiting the boundaries of our locatable area to ~0.5 km northeast of the vent (this can be seen in the locations as the artificial straight line cut off of events between TBTN and TBHS (Figure 3.13).

3.5.2 Challenges of seismic monitoring at PRVs

Increasing rates of seismicity are often observed as a short-term precursor to eruption. For example, LF swarms were observed preceding both the 1989-90 eruption and the main explosions of the 2009 eruption of Redoubt Volcano, Alaska (Stephens et al., 1994; Chouet et al., 1994; Buurman et al., 2013). Low-amplitude, LF swarms were observed before all large Vulcanian explosions during the 2005 eruption of Colima, Mexico (Varley et al., 2010). Increasing rates of seismicity, both VT swarms and LF swarms, were observed before the eruption of Mount Pinatubo in 1991 and were critical observations in the successful forecasting of the eruption (Harlow et al., 1996). High rates of VTs were observed before the 2006 eruption of Augustine Volcano, Alaska (Jacobs and McNutt, 2010). However, given the high and variable rates of seismicity at PRVs, such as Telica, forecasting eruptions based on increases in seismicity rate is difficult. We observe that the highest rates of seismicity at Telica during this study period occurred in November 2011 and March 2013, and the lowest rates occurred just after the eruptive episode onset, but before the most energetic phase of the episode (Figure 3.8). A further problem with monitoring seismicity at Telica is that due to the high variation in seismicity rates and the frequent explosion episodes, we are unable to establish what ‘normal’ seismic behaviour at Telica is, and determining deviations from ‘background’ is complicated by a lack of a stable and clear ‘background’ behaviour.
3.5.3 Low-frequency events at Telica

LF events dominate the catalogue at Telica and have rapid repetition rates. The maximum daily LF rate of 760 events on the 9th November 2011 indicates an average repetition rate of less than 2 minutes per event (Figure 3.11). Clearly with such high repetition rates the source process for these LF events must be highly repeatable. LF multiplets were observed at Telica in 1999-2000 (Rodgers et al., 2013) and the presence of these repeatable LF events indicates that the source process must be both repeatable and non-destructive. In most models of LF source processes, the LF wavefield is generated at the fluid-solid boundary by resonance of a fluid filled cavity, where seismic energy is trapped in the cavity by the impedance contrast between the fluid and solid (Chouet and Matoza, 2013, and references therein). Given the sustained high rates of degassing at Telica (Tenorio 1993 onwards) a possible trigger that could sustain such high repetition rates could be the unsteady or pulsatory transportation of either magmatic or hydrothermal fluids through a system of shallow conduits and/or cracks. The choked flow model (Chouet et al., 1994; Morrissey and Chouet 1997), where flow of superheated gas past a constriction in a crack accelerates fluid to supersonic speeds, chokes the fluid flow and generates a downstream shock wave; or a model where periodic rapid depressurisation of a gas filled crack triggers resonance of the crack (Nakano et al., 2003; Waite et al., 2008), could both generate LF seismicity at the rates observed at Telica. A similar high rate of LF seismicity, coupled with persistent degassing, is observed at Shishaldin Volcano, Alaska (Petersen, 2007) and is interpreted as choked flow in the hydrothermal system. The suggestion of a purely hydrothermal origin for LF events at Shishaldin is based on the lack of surface emissions of magma and the low SO$_2$ flux (Petersen, 2007). Evidence for a well-established hydrothermal
system at Telica comes from the presence of persistent high-temperature fumaroles in the crater and low-temperature fumaroles near station TBTN. Nearby mud pots and a geothermal power station at San Jacinto (~8 km from the vent) may also be related to the hydrothermal system at Telica. SO$_2$ flow rates of up to 530 Mg/day have been recorded (Mather et al., 2006) and long-term presence of incandescence in the crater strongly suggests that the top of the magma conduit is close to the crater floor, hence both magmatic and/or hydrothermal fluid transport are equally plausible as the source of LF seismicity at Telica.

3.5.4 High-frequency events at Telica

HF events are uncommon at Telica and their occurrence may signify a deviation from ‘normal’ fluid-flow-generated seismicity. At the beginning of September 2010 HF events made a sudden appearance, as part of a large swarm of events that began in late August 2010 (Figure 3.11). HF events at Telica have a high ratio of high to low frequency energy and may be similar to high-frequency microseismic events observed at volcanoes worldwide, known as volcano-tectonic earthquakes (VTs). VTs represent shear failure of rock in response to stress changes induced by changes in fluid pressures in a magmatic system (Roman and Cashman, 2006). Increasing pressure in a shallow magma chamber at Telica could result in increased stress in the magma chamber walls and brittle failure of the host rocks and generate the HF seismicity. Likewise a similar pressurisation could occur in a sealed hydrothermal system. No deformation is observed at Telica that can be related to eruptive processes; however, pressurisation of either a magmatic system or a hydrothermal system could be below the detection threshold of the GPS network (Geirsson et al., 2013). Alternatively, Telica is being actively sheared by tectonic...
stresses (Geirsson et al., 2013) and local faults within the edifice may be close to failure. Under such stress conditions an influx of new gas or new hydrothermal fluids could lower the effective normal stress on these local faults and promote shear failure (Byerlee, 1978). Shear fracture can also occur in response to stress changes in the conduit associated with magma withdrawal, as observed after magma removal during eruptions at Mt Pinatubo, Philippines (Harlow et al., 1996) and at Redoubt Volcano, Alaska (Power et al., 1994), and at Mount St Helens, a pressure drop in the magma chamber was suggested as the origin of deep earthquakes after the 1980 eruption (Moran, 1994).

3.5.5 Transition between open-system and closed-system degassing

Instead of the more commonly observed precursory increase in seismicity, a sharp decrease in seismicity is observed before the 2011 eruption of Telica. Seismicity rapidly shuts off in September 2010, increases slightly and then starts a five-month steady decline. Although we are unaware of any such long-term shut-off in seismicity before other eruptions, a short period of quiescence has been observed before explosive phases of eruptions and quiescence on an hour to month duration was observed before ~60 eruptions between 1979 and 1989 inclusive (McNutt, Pers. Comm. 2013) A 33 hr period of seismic quiescence was observed in the pre-explosion phase of the 1991 eruption of Mount Pinatubo, Philippines (Harlow et al., 1996) and a period of relative seismic quiescence occurred for a two-month period before the August explosion of the 1992 eruption of Crater Peak, Alaska (Power et al., 2002). At Galeras Volcano, Colombia, a complete cessation of LF events was observed in the 10 hrs before the March 1993 eruption (Fischer et al., 1994), and during the 2009 eruption of Redoubt Volcano, Alaska, gliding
harmonic tremor ceased ~30 seconds before some of the explosions (Hotovec et al., 2013). Assuming that LF seismicity at Telica is generated by transport of magmatic and/or hydrothermal fluids, a transition from open-system to closed-system degassing is a plausible mechanism for the seismic quiescence we observe before the 2011 eruption, as well as for the precursory transition from LF to HF seismicity (Figure 3.16, 3.17). A decrease in SO$_2$ flux was observed before the March 1993 eruption of Galeras Volcano, Colombia, (Fischer et al., 1996) and has been attributed to sealing of magmatic gas pathways below a sealed carapace (Fisher et al., 1996). At Soufriere Hills Volcano, Montserrat, cyclic decreases in SO$_2$ emissions preceded explosions in May-June 1999 and were attributed to changes in permeability in the conduit and dome, either resulting from rheological changes in cooling magma, or from the precipitation of minerals in gas pathways (Edmonds et al., 2003). At Telica, cooling-induced hydrothermal mineralisation in fracture networks and pore spaces could cause a reduction in the permeability of the gas pathways, effectively sealing the magmatic and/or hydrothermal degassing system (Figure 3.16) (Tenthorey et al., 1998). Ash analysis from the 2011 eruption indicates hydrothermally altered ash, and the presence of hydrothermal minerals such as gypsum, bassanite and anhydrite in the ash suggests sealing due to hydrothermal mineralisation (Geirsson et al., 2013). Variations in high-temperature fumaroles in the crater at Telica also support a sealing mechanism. The stable temperature measurements of ~200-300°C in 2010 drop to 122°C in February 2011, one month before the onset of the eruption (Geirsson et al., 2013). SO$_2$ measurements are unfortunately sparse during the proposed sealing period, however, mobile DOAS measurements from the 16$^{th}$ March 2011 indicate lower SO$_2$ values than those during early 2010 or during the energetic phase of the eruption in May-June 2011.
Figure 3.16. Interpretation of the open-system to closed-system transition hypothesis with sealing of degassing pathways. Open-system degassing is followed by a transition period and gradual sealing of the degassing system. The closed-system can then transition back to open-system degassing either with or without eruption.

(Geirsson et al., 2013) and support sealing of the degassing system before the main phase of the eruption. Alternatively, sealing of magmatic degassing could occur via collapse of interconnected bubble pathways or fracture networks at the top of a degassing magma conduit (Stevenson and Blake, 1998; Burton et al., 2007). Similarly, destabilisation and collapse of a foam layer at the top of a magma chamber beneath the conduit can cause the magma level in the conduit to drop (Jaupart and Verginolle, 1989; Stix, 2007), effectively destroying the LF source volume, or deepening the LF events such that their amplitudes are reduced below the
network detection threshold (Figure 3.17). In this model the eruption then represents the transition back from closed-system degassing to open-system degassing.

Figure 3.17. Interpretation of the open-system to closed-system transition hypothesis with a magma withdrawal mechanism. Open-system degassing is followed by a transition period of magma withdrawal. The closed-system can then transition back to open-system degassing either with or without eruption.

A cyclic pattern of seismicity rates is observed at Telica, both during this study period and during previous eruptive episodes. The 1999 eruption shows a similar pattern to the 2011 eruption, i.e. a decrease in seismicity months before the eruption, then a transition to high rates of predominantly LF events after the eruption. In this study the period of declining seismicity throughout 2012 was followed by a sudden increase in seismicity (Figure 3.8) and a
small volume ash explosion in January 2013. However, other periods of observed decreased seismicity did not culminate in explosive activity. For example, in September 2011 seismicity declined and was followed by a swarm of high seismicity, and then again in January-February 2012 the seismicity decreased and was followed by a large swarm of events, but in neither of these cases was eruptive activity observed after the seismic minimum, although unobserved ash emissions could have occurred at night. These observations suggest that the mechanism for ‘closing’ the system must be capable of ‘opening’ the system again both with and without significant eruptive activity. However, we note that the decreases in seismicity that did not culminate in observed eruptive activity were all shorter than those that did, and perhaps in those instances the system re-opened before conditions were met for a phreatic eruption.

**3.5.6 Implications for eruption forecasting**

The data presented here indicate that a decrease in the rate of seismicity precedes phreatic-to-phreatomagmatic eruption episodes at Telica. However, these precursors are not unique signals of eruptive activity, as not every period of reduced seismicity culminates in an eruption. Our observations suggest that the observed patterns of geophysical unrest are driven by a transition from open-system to closed-system degassing. Although the cause of these transitions is unclear, multidisciplinary observations surrounding the 2011 eruptive episode suggest sealing of the hydrothermal system as a potential mechanism for this transition. Swarms of LF and HF seismicity, followed by periods of decreased seismic activity and a cessation of LF events together suggest an increased likelihood of an eruption, but the system also appears able to transition back to open-system degassing without a significant eruption. These observations
suggest that despite the highly variable seismicity rate, some phreatic eruptions at Telica are preceded by a precursory drop in seismicity. The unusual nature of this precursory drop in seismicity highlights the need for continued investigation into seismic processes at PRVs, and in particular, the need for further multidisciplinary observations.

3.6 CONCLUSIONS

We analysed seismic characteristics from a three-year deployment of a broadband seismic network on Telica Volcano, Nicaragua. We demonstrate that seismicity rates at Telica are highly variable and that seismicity is dominated by events with low-frequency energy. Analysis of seismicity rates surrounding the 2011 phreatic eruption of Telica indicates a swarm of LF and HF events preceded a rapid shut off in seismicity approximately six-months before the eruptive episode. We then observe a brief increase in seismicity before a long steady decline in event rates, which reached a minimum at the eruption onset. We observe a progressive loss of events with lower-frequency energy during this decline in seismicity before the eruption. Event rates increased towards the end of the eruption and there is then a repeated pattern of seismic shut-off and seismic swarms with changes to the frequency content of the events. These observations indicate a highly variable source of seismicity and could indicate changes in the magmatic and/or hydrothermal system at Telica.

These observations have important implications for eruption forecasting at Telica and other PRVs, as typical short-term increases in seismicity before eruptions are not observed, but rather we observe a decrease in seismicity before eruptive activity. However, not all periods of seismic
shut-off culminate in eruptive activity, which highlights the difficulty of seismic monitoring at PRVs. We propose that these repeated patterns of high-to-low seismicity represent transitions between open-system and closed-system degassing. New gas monitoring instrumentation on Telica may provide further evidence to assess this hypothesis.

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CHAPTER FOUR:

DEVELOPMENT OF THE JAVA PROGRAM ‘PEAKMATCH’ FOR MULTIPLE ANALYSIS OF VERY LARGE SEISMIC DATASETS AT TELICA VOLCANO, NICARAGUA.

ABSTRACT

Waveform cross-correlation (multiplet analysis) is increasingly being applied to volcanic-seismic data sets, but such analysis is often restricted by computational limitations. We developed a program called ‘peakmatch’ that can efficiently handle cross-correlation of very large seismic data catalogues. Our code utilises a fast approximation process to pre-select candidate pairs for cross-correlation. Once the candidate pairs are selected, full FFT cross-correlation is carried out on all the candidate pairs. An analysis phase is first necessary to tune the parameters to a specific data set, to minimise false-candidates and false-negatives, and to reach a balance between accuracy and running time. We tested our method against the widely accepted two-stage method of Petersen (2007) and Thelen et al. (2010) and find significant improvements in terms of numbers of connected events identified. Our program performed well in terms of processing time and was able to handle a dataset of over 200,000 events in ~ 13 hrs.
We present the results of multiplet analysis of data from deployment of a seismic network on Telica volcano, Nicaragua, from 2010 to 2013, including surrounding a period of eruptive activity in 2011. From the initial dataset of ~217,000 events we identified over 51,000 connected events, of which there were ~9500 multiplets with two-or-more events. We observe that periods with high rates of new multiplet formation correspond to periods of increased daily event rates and higher percentages of daily events that occur as part of a multiplet. Likewise we observe that periods of low rates of new multiplet formation correspond to low daily event rates and low percentages of daily events that occur as part of a multiplet, and explosive periods occur at the end of these periods of low waveform correlation. We suggest that periods of high rates of multiplet formation relate to periods of open-system degassing and that periods of low multiplet formation relate to periods of closed-system degassing at Telica.

4.1 INTRODUCTION

The identification of repeating earthquakes with similar waveforms (“multiplets”) has many applications in the analysis of volcanic earthquake data. A repeated seismic waveform implies that the source process of those events is repeatable and non-destructive, and that the location of the event remains stable (Geller and Mueller, 1980). Multiplets occur to some extent at most volcanoes (West, 2013), but the creation, destruction and duration of individual multiplets can be used to study behaviour surrounding eruptions; for example, to evaluate stress changes or to constrain the depth of explosion events (Buurman and West, 2010; Thelen et al., 2011; West 2013). Multiplets can be used to improve locations through stacking or cross-correlation to
obtain relative arrival times (Got et al., 1994; Battaglia et al., 2003), which is especially useful for the small-amplitude, emergent events that are common to many volcanic datasets. Multiplet analysis thus has the potential to be an intrinsic part of the volcano seismologist’s toolbox; however, many studies cite computational limitations when analysing multiplets (Petersen 2007; Thelen et al., 2010; Thelen et al., 2011; Ketner and Power, 2013).

Telica Volcano, Nicaragua is a persistently restless volcano (PRV) (Stix, 2007) that typically produces hundreds of seismic events per day. Since 2010 a broadband seismic network has been running on Telica (Figure 4.1) and over 200,000 events have been detected (see Chapter 3). Cross-correlation of so many events by traditional means is computationally unfeasible. Therefore we sought to develop a program, ‘peakmatch’, that would allow us to cross-correlate seismic waveform data from volcanoes with very high levels of seismicity, such as Telica. We also added a mode of operation to peakmatch that would output spectral data for large data sets. We developed a secondary program, ‘graph-connectivity’, to identify multiplets from the potentially millions of cross-correlation event pairs output by our peakmatch program.

4.2 BACKGROUND AND MOTIVATION

4.2.1 Large scale cross-correlation computation

Cross-correlation is computationally expensive and large data sets can rapidly become impossible to work with. The efficiency of cross correlation algorithms is considered a Big-O(N^2) problem (where N = total number of events) in terms of the performance time of the algorithm (Black, 2004) (i.e., for every factor of two increase in events, there is a factor of four increase in
the number of cross-correlation operations required. The number of cross-correlation operations is $N^2/2$, therefore for a catalogue of two-thousand events, two-million operations are required; and while this number of calculations presents no problem.

**Figure 4.1.** Location of Telica Volcano and seismic station TELN/TBTN. Inset map: Central America (right) and major volcanic centres of Nicaragua (left).
for some of the excellent programs already written, such as the GISMO suite (Reyes and West, 2011), larger data sets cannot be so easily handled. Seismic data catalogues of hundreds of thousands of events are not uncommon at volcanoes (Ketner and Power, 2013), and for a catalogue of two-hundred thousand seismic events, ~20-billion operations are required. Assuming a computation time of 1 millisecond per cross-correlation, the full 20-billion operations would take ~231 days to complete. A method developed by Petersen (2007) and Thelen et al. (2010) overcomes some of the computational limitations of large data sets by correlating all events within a given period of time (e.g., within a 24 hr period), compiling stacked events from each given period of time and then cross-correlating all the stacks across the entire study period. This two-stage method significantly reduces the number of operations necessary; however, events that only occur once during the chosen time interval, or multiplets that exist entirely within the chosen time interval, will be missed.

4.2.2 Family identification

Once the problem of cross-correlating large datasets has been solved, a secondary challenge is how to group events based on the potentially millions of cross-correlation outputs. There are various approaches for defining a multiplet. One approach is to identify a master event and match correlated events to the master event. A master event can be chosen as the event with the most connected events above a certain threshold (Green and Neuberg, 2006), or it can be chosen based on average cross-correlation values from correlation with all other events (Petersen, 2007). Another method of family selection uses a hierarchical clustering technique that progressively links pairs until clusters are found at a given threshold (Rowe et al., 2002;
Buurman and West, 2010). An event should only belong to one family, so as families are formed the events within that family are removed from the pool of available connected events. This leads to the creation of orphaned events (i.e. events that were connected to events within another family, but not connected to the master event), and once their linked pair has been assimilated into a family, the event is now unlinked to any other event in the remaining pool.

4.2.3 Other multiplet studies

Multiplet studies have typically been undertaken for volcanoes with lava-dome eruptions, such as Bezymianny, Russia; Mount St Helens, USA, and Soufriere Hills Volcano, Montserrat (West 2013; Thelen et al., 2011; Green and Neuberg 2006). Precursory multiplet swarms (i.e. swarms of events containing many correlated events) at these systems have been interpreted as gas-charged pressurisation in a closed-system degassing regime (Thelen et al., 2011). Multiplet swarms have also been observed at Shishaldin, Alaska, a PRV with similar eruptive and seismic activity to Telica (Petersen, 2007). Here, multiplet activity is interpreted as choked flow of gas (Morrissey and Chouet 1997) in the hydrothermal system at Shishaldin (Petersen, 2007). Multiplet analysis of the 1999 eruption of Telica (Rodgers et al., 2013) interprets the rapid creation and destruction of multiplets as the formation of unstable degassing pathways during a transition from open- to closed-system degassing.
4.3 PROGRAM DESCRIPTION

4.3.1 Peakmatch program overview

To cross-correlate two events, the sliding dot product of the two time-series vectors is calculated. This results in an $O(M^2)$ performance per event pair and $O(N^2 \times M^2)$ performance for all event pair calculations (where $N =$ total number of events and $M =$ number of data points per event). A significant improvement in performance can be gained by instead using FFT-based cross-correlation. In this case the cross-correlation calculation becomes a multiplication in the frequency-domain, resulting in $O(M)$ operations per event pair, and $O(M \times N^2)$ performance for all event pair calculations. However, this approach is still too computationally expensive for large data sets, and therefore in our code a fast-approximation stage is utilised in the time-domain to pre-select events for subsequent FFT-based cross-correlation.

Our code ‘peakmatch’ utilises a fast approximation process to pre-select candidate pairs for cross-correlation (Figure 4.2). The main assumption behind this process is that the number of candidate pairs identified in this approximation stage is significantly smaller than the total $N^2/2$ pairs, where $N =$ total number of events. This method works best for data-sets where the match density is sparse (i.e., less than one pair in a hundred event pairs should cross-correlate above a given threshold). The fast approximation (peakmatch) stage of the process uses three optimisations:

a) Top peak alignment: Two events are more likely to have a high cross-correlation coefficient if their peaks and troughs occur at the same time. The largest dot products occur when the largest amplitude peaks and troughs are aligned. Figure 4.3 shows a 4
second section of an example pair of events that have a cross-correlation coefficient of ~0.8. The largest amplitude peaks of these two events are offset by 6 samples (Figure 4.3a) and the largest dot product value occurs at a 6 sample offset (Figure 4.3b). For the optimisation process, the peaks and troughs of each event are pre-calculated and ordered by amplitude. This was done by first subtracting the mean from the waveforms and then iteratively finding the maximum and minimum values up to a given number of maximum/minimum values. When calculating the sliding dot product of event pairs, only the dot product for the top user-defined ‘K’ peaks/troughs are calculated, rather than calculating the dot product for every offset step. This rapidly reduces the number of calculations per event pair, and provided K is set to be significantly smaller than $M^{1/2}$, can result in $O(M)$ performance.

b) Sub-sampling: By only calculating the dot product of the peak-aligned events at a given number of data points (‘S’), the calculation speed is improved by a factor of S (sampling stride).

c) Amplitude threshold: The cross-correlation coefficient is dominated by multiplication of the largest peaks and troughs, yet most of the calculation time is spent multiplying the existing low-amplitude noise of the signal. By ignoring low-amplitude noise values and only calculating the dot-product for data points that are higher than some fraction of the maximum amplitude, considerable gains can be made in performance.
Figure 4.2. Illustration of the stages of processing of event pairs via the *peakmatch* method. a) initial stage: fast-approximation of all events pairs, b) 8 candidate pairs identified for full FFT cross-correlation, c) Full FFT cross-correlation of the 8 candidate pairs results in 5 event pairs above the final-threshold value.

Figure 4.3. Illustration of the top peak fast-approximation stage. a) 4-second waveform (200 samples at 50 Hz) from two events from April 2010 with cross-correlation coefficient 0.8. Events have been normalised to amplitude of 1. The top peak of each event are separated by 6 samples. b) the dot product of the events at each offset. The largest peak in the dot product occurs at a 6 sample offset.
Further improvements in performance time can be achieved by cropping the waveform. We did not want to rely on picked first arrivals to crop the waveforms, as this would limit this program for use with only those data that contain picks. Instead we chose to crop the earthquake by searching a user-defined window for the largest peak-to-peak amplitude, then cropping the waveform to a user-defined amount before and after this maximum peak.

These optimisations introduce a certain amount of error into the final cross-correlation output list. There will be events (false-candidates) that are considered as candidate pairs after the fast approximation stage, but that do not correlate well when full FFT cross-correlation is performed. There will also be events (false-negatives) that would correlate well during the full FFT cross-correlation stage, but were not considered as candidate pairs as they do not meet the candidate pair selection criteria, and hence are discarded. False-candidate events are discarded in subsequent FFT cross-correlation stages, but with an increased amount of processing time. However, false-negatives are lost permanently from the final output. Hence an analysis phase is essential to tune the parameters to a specific data set, to minimise false-candidates and false-negatives and to reach a balance between an acceptable loss of false-negative events and running time. A higher false-candidate rate will increase the post-processing time, but a higher false-negative rate means a loss of events that belong in the final catalogue.

4.3.2 Peakmatch control parameters

Program operation is controlled entirely by a configuration file ‘xcorr.conf’ (See Appendix E). The mode of operation is specified in this file, as are paths to data directories. All input files are
single column text files. This format was chosen rather than any program specific data types (e.g., SAC, MiniSEED) to make the program more versatile for any data input. Input files need to be of the same sample length and this length is specified in this file. Cropping can be enabled or disabled; if enabled there is a user-defined range to search for maximum peak-to-peak amplitudes and a user-defined crop window before and after the maximum peak. The three optimisation parameters (as discussed in section 4.3.1) are then specified (i.e., top k peaks, sampling-stride and top-amplitude-threshold). Next, candidate-threshold is set; this is not a true cross-correlation threshold value, but an indicator of similarity based on the approximations, which affects the number of candidate pairs passed on for post-processing. The final-threshold cross-correlation coefficient is then specified, and only events that have a cross-correlation coefficient higher than this value will be output in the final post-process stage. Specific system settings can then be input (i.e., number of processing cores, and memory-cache size for FFT calculations). Events can be normalised by subtracting the mean amplitude from all readings. Next various settings for additional spectral analysis modes of operation are set, such as band-width of dominant frequency peaks, sample rate, filter bands, number of frequency peaks, spectral amplitude bands and spectrogram time-window sizes.

4.3.3 Peakmatch program operation

4.3.3.1 Phase 1: Analyse

A sample of 1000 events is analysed using both peakmatch and full FFT cross-correlation. The results are compared and performance statistics are output (i.e. number of false-candidates, number of false-negatives and an estimation of processing time for both the peakmatch stage
and the post-process stage for the full dataset). Crop parameters, top ‘K’ peaks, sampling-stride, amplitude threshold, candidate-threshold and final-threshold values should all be tested to find specific parameters for the target dataset that give optimal output in terms of minimal false-negatives vs. reasonably short processing time.

4.3.3.2 Phase 2: Peakmatch

The fast-approximation stage (as outlined in section 4.3.1) is performed using the parameters chosen from the analysis phase. Events are considered as a candidate pair if they match above the candidate-threshold. A higher candidate-threshold lets more candidate pairs pass to the post-process stage, at a cost of increased post-processing time.

4.3.3.3 Phase 3: FFTprecache

The final FFT cross-correlation of all candidate pairs calculates the complex dot product of the Fourier transform of one event with the Fourier transform of the reverse of the second event. To speed up this process, the FFT of every event and the FFT of the time-reverse of every event is calculated and stored in a large memory-mapped file.

4.3.3.4 Phase 4: Post-process

Maximum cross-correlation values of each candidate pair output by the peakmatch stage (Phase 2) are calculated. The complex dot product of the FFT of event A and the FFT of the time-reverse of event B is calculated from the pre-cached FFT values calculated in Phase 3. The inverse Fourier transform is then calculated, and the highest value of the real components is
the cross-correlation of the two events. Event pairs are written to an output file if their cross-correlation value is above the final-threshold value specified in the control parameters. This final-threshold value should be chosen based on either visual comparison of sample waveforms, or on the statistical distribution of cross-correlation coefficients of a test data set.

4.3.3.5 Additional modes of operation:

a) Bruteforce: All events within a specific directory can be cross-correlated and event pairs above the final-threshold will be output. The FFT pre-cache stage needs to be performed before the bruteforce mode. This mode should not be used on very large datasets (i.e. more than ~10,000 events).

b) FFT dominant frequency. This mode was developed to output spectral information on individual events; no cross-correlation is performed in this mode. The dominant frequency of every event is calculated from the FFT of the waveform (with or without time-domain cropping and with or without bandpass filtering). A user-defined number of frequency peaks can be output, and a user-defined bandwidth can be specified between each frequency peak (e.g., if the dominant frequency peak of an event was found at 1 Hz, a bandwidth of 0.5 Hz could be set such that the next highest frequency peak is returned excluding a 0.5 Hz window above and below 1 Hz). Maximum peak-to-peak time-domain amplitude of each event is output after the dominant frequencies. Mean spectral amplitudes within a series of user-defined frequency bands can then be output.
c) Plot 1D and 2D. Spectral information from user-defined spectral amplitude bands can be displayed rapidly either via a 1D PSD plot in either a ‘tiny’ or a normal format, or via a 2D spectrogram with user-defined time windows.

**4.3.4 Graph connectivity program**

A separate program, 'graph-connectivity', was developed to extract information from the potentially millions of cross-correlation event pairs output by *peakmatch*. This uses an undirected graph, where the most connected node is identified (a master event) and it, along with all its immediate connections are extracted. The graph is then re-ordered and the process repeated until all connected nodes are extracted. This method ensures that each event only belongs to one family. As with any method for finding families the problem of ‘orphaned’ events occurs. These are events that do not directly connect to any of the master events, but will be connected to family members of the master events. After removal of the master event and its respective family, the orphaned event no longer has a connection within the graph and now belongs to no family at all. These orphaned events are output in the final connected output as individual events that do not belong to a multiplet.

**4.4. DATA ANALYSIS**

**4.4.1 Data analysis overview**

We analysed three different data catalogues in this study. The first comes from the Instituto Nicaraguense de Estudios Territoriales (INETER) single-station short-period (1 Hz) seismic station TELN (Figure 4.1) and spans from the 16th of August 1999 to the 31st of March 2000.
Rodgers et al. (2013) previously analysed this catalogue using the two-stage cross-correlation method of Petersen, (2007) and Thelen et al. (2010). This re-analysis thus allows a direct comparison between the widely accepted two-stage method and the peakmatch method. For our second analysis, we expanded the data catalogue used in the first analysis to incorporate previous months of data and to extend our multiplet analysis to before the onset of the 1999 eruption (which started in May 1999). Data for this second analysis come from the same station, TELN, and span the 1st of January 1999 to the 31st of March 2000 (note that events from the 16th of August 1999 to the 31st of March 2000 are identical to those analysed in the first study). Data for the third analysis come from the vertical component of a single-station broadband (30 second) instrument (TBTN) (co-located with TELN, – Figure 4.1) from the Telica Seismic and Deformation (TESAND) network (See Chapter 3 for details on event detection of the TESAND network). This catalogue runs from the 1st April 2010 to the 18th March 2013.

4.4.2 Analysis 1: Comparison of peakmatch method to two-stage method

Previous multiplet analysis of seismic data surrounding the 1999 eruption of Telica (Rodgers et al., 2013) was carried out using the Matlab GISMO suite (Reyes and West, 2011), following the method of Petersen (2007) and Thelen et al., (2010). Multiplets in this previous study were identified by cross-correlating all events in each 24 hr period. Daily stacks were produced by identifying a master event (the event with maximum mean cross-correlation value), and stacking all events correlating with the master event above a threshold of 0.7. This process was repeated until no more events pairs existed above the 0.7 threshold. Once daily stacks were created for all 24 hr sections in the study period, all the daily stacks from the entire study
period (291 in total) were then cross-correlated against each other. Multiplets were found using the same master-event method as for the 24 hr sections, this time with a threshold value of 0.8. Thirty-seven multiplets were identified using this method, containing a total of 1770 individual events (Figure 4.4b). Orphaned events occur when all events that are connected to that event have been assigned to other multiplets. We identified a further 596 events that were considered orphaned events and not part of the 37 identified multiplets, making a total of 2366 connected events for this method.

Reanalysis of the same seismic data catalogue allows us to compare multiplets identified using our \textit{peakmatch} method with the results of the two-stage analysis, and thus provides a test of our new program. Before we analysed the full data set we performed a preliminary test of the first stage of the two-stage method against \textit{peakmatch} to see if the same events were identified within the 24 hr periods. For this test, analysis of two different 24 hour periods (19\textsuperscript{th} September 1999 and the 20\textsuperscript{th} September 1999) that contained known multiplets was performed using both methods. On both days the two methods identified identical multiplets, although the identified master event was not the same for all multiplets between the two methods. For the analysis of the full seismic data catalogue, we expect there to be slight differences between the final multiplets identified in both methods as the methods are subtly different, both in how events are cross-correlated and in how multiplets are defined. Cross-correlation threshold values are not directly comparable across the two methods as final multiplets produced in the previous study (two-stage method) were cross-correlated from stacked waveforms, which improved their signal-to-noise ratio and so a higher final-threshold
Figure 4.4. INETER data from August 1999 to March 2000 and the comparison of the two-stage method with *peakmatch*. a) Daily event rates, b) Multiplet timeline identified by two-stage method. Each event within a multiplet is plotted as a black diamond and multiplet life-spans are plotted as grey horizontal lines, c) Multiplet timeline identified by *peakmatch*. Each event within a multiplet is plotted as a black circle. There are too many multiplets present to display life-span information. Explosive periods are marked by grey boxes/vertical lines and periods with no data are marked by diagonal shading.
value of 0.8 was more appropriate in that study. To improve performance times in peakmatch, we crop waveforms to a 12 second window around the maximum peak-to-peak amplitude, which may improve the cross-correlation values of event pairs and increase the number of correlated events above a given threshold.

A final-threshold value of 0.7 was chosen for our peakmatch program from analysis of the frequency distribution of cross-correlation coefficients. Two different histograms of cross-correlation coefficients were calculated, firstly from a random sample of 1000 events, and secondly using all 1137 events from a 10 day period with known multiplets (identified from the previous study). The frequency distribution plot of the random 1000 events (Figure 4.5a) shows the correlation-coefficient value of 0.7 to be well above the normal distribution curve. In the frequency distribution plot of the 10 day period with known multiplets (Figure 4.5b), the set of correlation-coefficients that belong to the multiplets can be clearly seen as the second peak of this bimodal distribution, here the correlation-coefficient of 0.7 is within the second mode. Hence our choice of 0.7 as a final-threshold is valid for identifying events that correlate above the normal distribution curve.
Figure 4.5. Threshold tests for INETER data. a) Frequency distribution of the cross-correlation coefficients of 1000 randomly selected events, b) Frequency distribution of the cross-correlation coefficients of all 1137 events in a 10-day period with known multiplets. Black arrows indicate the selected cross-correlation threshold value (0.7) for our analysis.

The data catalogue analysed in this study contains over 16,000 events and full cross-correlation of this dataset would require over 130 million operations. In the analysis phase of the program, a sample of 1000 randomly chosen events were tested using parameters in Table 4.1 versus a full cross-correlation of these events. Iterations of the analysis phase were carried out until parameters were found that gave a minimum false-negative rate and an acceptable false-candidate rate and processing time estimation. The final parameters from this iteration (Table 4.1) produced a false-candidate rate of 287% and a false-negative rate of 0% (Table 4.2). This low false-negative rate means that for extrapolation to the full data set, we have confidence that almost no events were discarded during the candidate selection phase. *Peakmatch* selection using the parameters in Table 4.1 identified ~2.3 million candidate pairs above the candidate-threshold. Post-processing of these ~2.3 million candidate pairs resulted in ~637,000 correlated pairs above the final-threshold. *Graph-connectivity* identified 8340 connected events.
within the final post-processed event pairs and the dominant family identified within the final 8340 events contained 946 events. Due to the process of removing the most connected multiplets, the multiplets extracted during the graph-connectivity process become progressively smaller and eventually we get orphaned events. Of the 8340 total connected events, 1358 were orphaned events. We identified 594 multiplets with 2 or more events, which comprised 6982 events in total (~84% of the connected events).

**Table 4.1: Input control parameters**

<table>
<thead>
<tr>
<th></th>
<th>Analysis 1 INETER – comparison</th>
<th>Analysis 2 INETER – full data set</th>
<th>Analysis 3 TESAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak range window (s)</td>
<td>35 to 55</td>
<td>35 to 55</td>
<td>5 to 40</td>
</tr>
<tr>
<td>Crop range (s)</td>
<td>-4 +8</td>
<td>-4 +8</td>
<td>-4 +8</td>
</tr>
<tr>
<td>Top K peaks</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Sample stride</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Top amplitude threshold</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Candidate threshold</td>
<td>0.55</td>
<td>0.55</td>
<td>0.6</td>
</tr>
<tr>
<td>Final threshold</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Table 4.2: Performance metrics**

<table>
<thead>
<tr>
<th></th>
<th>Analysis 1 INETER – comparison</th>
<th>Analysis 2 INETER – full data set</th>
<th>Analysis 3 TESAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of events</td>
<td>16,129</td>
<td>29,397</td>
<td>217,101</td>
</tr>
<tr>
<td>False candidate %</td>
<td>287</td>
<td>270</td>
<td>571</td>
</tr>
<tr>
<td>False negative %</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Run time</td>
<td>1 hour 10 minutes</td>
<td>6 hours 45 minutes</td>
<td>13 hours 20 minutes</td>
</tr>
<tr>
<td>Candidate pairs</td>
<td>2,353,729</td>
<td>14,610,084</td>
<td>63,055,408</td>
</tr>
<tr>
<td>Post-processed pairs</td>
<td>636,798</td>
<td>3,795,183</td>
<td>10,482,297</td>
</tr>
<tr>
<td>Number of connected events</td>
<td>8340</td>
<td>17,633</td>
<td>51,656</td>
</tr>
</tbody>
</table>
We chose to plot only those multiplets that contained two or more events, i.e. ignoring the orphaned events (Figure 4.4c). The rates of multiplet formation identified by the two methods show a similar overall trend, but have subtle differences. Multiplets are ordered by appearance of the first event in the multiplet and the daily event rate is plotted for comparison. Multiplets 1 to ~ 25 identified with the *peakmatch* method appear to exist at the start of the data period, multiplets ~ 25 to ~ 90 then appear rapidly over the next two weeks. The repetition rate of some of the events in multiplets 25 to 90 is sufficiently long that they may have existed before the start of the time period analysed, i.e. previous events in the multiplet may have occurred before the 16th August 1999, however, some multiplets have sufficiently rapid repetition rates that they would have been observed in the period before the onset of the first event in the multiplet. Multiplets identified with the two-stage method show a rapid onset of multiplets at the end of August 1999 and throughout September 1999. There is some overlap with the rapid onset of events from the *peakmatch* method (multiplets ~ 90 to ~ 125), but most of the rapid onset of events in the two-stage method occurs in September 1999, after a shallowing of the onset rate of multiplets from the *peakmatch* method. There are similarities between the two methods, in that many of the events from the multiplets that begin in the August-September 1999 period cease during the October 1999 explosions. Similarly, there are very few multiplets identified by either method that begin between October 1999 and January 2000, however, this may be explained by an overall decrease in event rate during this time. There is a pronounced post-eruption increase in multiplets identified from the *peakmatch* method as compared to the two-stage method where there are very few new post-eruption multiplets. This may be because
many of the post-eruption multiplets identified in the peakmatch method have repetition rates longer than 24 hrs.

4.4.3 Analysis 2: INETER data from 1st January 1999 to 31st March 2000

Multiplet analysis of over 29,000 events from the 1st of January 1999 to the 31st March 2000 was performed with peakmatch using the parameters in Table 4.1. As ~16,000 of these events were identical to the analysis in section 4.4.2, we kept the same final-threshold values determined from correlation-coefficient distribution histograms (Figure 4.5). Iteration of the analysis phase was carried out until we found a minimal false-negative rate and an acceptable false-candidate rate and processing time estimation. The final parameters from this iteration (Table 4.1) produced a false-candidate rate of 270% and a false-negative rate of 0% (Table 4.2). Similarly to the data in analysis 1, this low false-negative rate for the 1000 sample set gives us confidence that we have missed very few events in correlation of the full data catalogue. The peakmatch fast-approximation stage identified over 14.6 million candidate pairs, of which approximately 3.8 million event pairs had full correlation-coefficients above the final threshold. 17,633 connected events were identified from the 3.8 million event pairs, and the dominant family contained 4087 events. 3192 of the events were orphans. Not counting orphaned events there were 985 identified multiplets, with 442 of these containing only two events.

We chose to only display the 985 multiplets with 2 or more events, i.e., ignoring the orphaned events (Figure 4.6), which in total contained 14,441 connected events (~ 82% of the connected events). There are only 37 new multiplets that begin during the period between the 1st of
January 1999 and the 17\textsuperscript{th} of January 1999, but then between the 18\textsuperscript{th} of January 1999 and the end of January 1999 ~ 200 new multiplets appear. This sudden jump in the onset of multiplets corresponds to the sudden increase in daily event rates (Figure 4.6a). There is a slight acceleration in the rate of onset of new multiplets around the 15\textsuperscript{th} February 1999 (Figure 4.6b) which corresponds to the start of the rapid decline of events in February 1999. At the end of February 1999 there is a distinct change in the rate of creation of new multiplets, ~ 400 multiplets began between mid-January 1999 and the end of February 1999, but only ~30 multiplets then began between the end of February and the start of the data gap on the 13\textsuperscript{th} of May 1999, however, event rates are very low. This catalogue is affected by significant data gaps; however, several multiplets do span this three month data gap (from the 13\textsuperscript{th} of May 1999 to the 16\textsuperscript{th} August 1999). The period from the 16\textsuperscript{th} of August 1999 to the 31\textsuperscript{st} of March 2000 shows overall similarities with the first analysis (section 4.4.2). This suggests that many of the multiplets that began at the start of the Analysis 1 period did in fact begin at that time; however, there are also multiplets that originated earlier that persist throughout the entire eruptive period.

4.4.4 Analysis 3: TESAND data from 1\textsuperscript{st} April 2010 to 18\textsuperscript{th} March 2013.

Multiplet analysis of 217,101 events recorded between the 1\textsuperscript{st} of April 2010 and the 18\textsuperscript{th} of March 2013 was carried out with \textit{peakmatch}, using the parameters in Table 4.1. A final-threshold value of 0.8 was initially chosen by plotting the frequency distribution of cross-correlation coefficients of ~ 1100 events from a randomly chosen ten-day period from the 1\textsuperscript{st} of October 2010 to the 10\textsuperscript{th} of October 2010. This frequency distribution (Figure 4.7a) shows that
Figure 4.6. Multiplet timeline of INETER data from January 1999 to March 2000. a) Daily event rate, b) Multiplet timeline, each event within a multiplet is plotted as a black circle. Explosive periods are marked by grey boxes/vertical lines and periods with no data are marked by diagonal shading.
the chosen final-threshold of 0.8 is well above the normal distribution curve. After identification of multiplets, the frequency distribution of correlation-coefficients from the ~1400 events from a three-day period (5\textsuperscript{th} of September 2010 to 7\textsuperscript{th} September 2010) that contained known multiplets was plotted for comparison (Figure 4.7b). This bimodal frequency distribution confirms that using a final-threshold value of 0.8 would identify events only outside of the normal distribution curve. Iteration of the analysis phase resulted in the final parameters in Table 4.1 and produced a false-candidate rate of 571% and a false-negative rate of 0% (Table 4.2). As in the previous two analyses, this low false-negative rate for the 1000 sample set gives us confidence that we have missed very few events in correlation of the full data catalogue.

Over 63 million candidate pairs were identified by the fast-approximation phase. Full cross-correlation of these 63 million pairs resulted in approximately 10.5 million event pairs that correlated above the final threshold. From the 10.5 million event pairs, 51,656 connected events were identified. The largest family contained 4882 events and 7188 events were orphaned events. Not counting orphaned events there were 9460 multiplets (of two or more events), and of these, 7939 contained only two events.

We chose to only display the 9460 multiplets with two or more events (Figure 4.8), which in total contained 44,468 connected events (~86% of the connected events). The study period for this analysis starts on the 1\textsuperscript{st} April 2010 and there are ~250 multiplets that are active over the first month, many of which remain active throughout the entire study period. As discussed for the data in the previous datasets, some of these multiplets may have had event repetition rates
Figure 4.7. Threshold tests for TESAND data. a) Frequency distribution of the cross-correlation coefficients of ~ 1100 events from a randomly selected 10-day period, b) Frequency distribution of the cross-correlation coefficients of ~ 1400 events from a three-day period with known multiplets. Black arrows indicate the selected cross-correlation threshold value (0.8) for our analysis.

Slow enough that events belonging to this family could have occurred before the start of the study period, however, there are many events in this one-month period that have repetition rates sufficiently high that they can be considered to have begun at this point. Between May 2010 and July 2010 there is a definite change in the rate of onset of new multiplets, as only ~100 new multiplets begin during this period. At the beginning of July 2010 there is a sudden increase in the number of new multiplets, ~ 1000 multiplets begin between July and the end of August. Then at the end of August 2010 there is another increase in the number of new multiplets, as ~ 800 new multiplets begin in a two-week period. This onset of new multiplets
Figure 4.8. Multiplet timeline of TESAND data from April 2010 to March 2013. a) Daily event rate, b) Multiplet timeline, each event within a multiplet is plotted as a black circle. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey.
corresponds to a seismic swarm in late August 2010 (Figure 4.8a). On the 10th of September 2010 there is another sudden reduction in the rate of onset of new multiplets. In March 2011 an eruptive episode began at Telica, comprising a period of weak ash emissions, followed by a more energetic period of explosions that began on the 8th May 2011 (Geirsson et al., 2013). Multiplet activation in the six-month period before the eruption onset in March 2011 was low, corresponding to a period of low daily event rates. Six-days after the start of the energetic phase of the eruption, multiplet activation starts to increase, corresponding to a period of increasing seismicity, during this period there is also a repetition of previously active multiplets. A steady rate of multiplet activation occurs until the end of 2011, with ~ 5000 multiples activated over this seven-month period. There are three seismic swarms following the eruptive episode, in September 2011, November 2011 and February 2012, and increases in multiplet activation occur during these three swarms. Also during these swarms, we again observe a repetition of many previously active multiplets. Between June 2012 and the end of the study period in March 2013 only ~500 new multiplets begin, again this corresponds to a low event rate.

Waveforms from three example multiplets are displayed in Figure 4.9. Each multiplet is displayed as four super-imposed waveforms that were selected randomly from the multiplet (Green and Neuberg, 2006). Multiplet A represents the largest multiplet found in the catalogue and contains 4883 events. The multiplet was active for the entire study period. The first event in the multiplet occurs on the 1st April 2010, the first day of the study period, and the last event occurs on the 18th March 2013, the last day of the study period. The multiplet does not occur
every day, but varies from no events on some days, to a maximum of 149 events on the 16th November 2013. The average peak frequency of all the events within this multiplet is 4.2 Hz. The second multiplet (Multiplet B) was randomly chosen from the group of multiplets that began in late-August 2010 (Figure 4.8). This multiplet starts on the 24th August 2010 and finishes on the 1st September 2010. It contains 52 events and those events have an average peak frequency of 7.1 Hz. The third multiplet (Figure 4.9, Multiplet C) was randomly chosen from the group of multiplets that began at the start of the energetic phase of the eruption in May 2011. This multiplet starts on the 7th June 2011 and finishes on the 15th July 2011. It contains 46 events and those events have an average peak frequency of 4.3 Hz.

To assess if the rate of occurrence of multiplets is solely due to changes in event rates we looked at variations in percentage of multiplets (Thelen et al., 2011). We looked at the percentage of events in each day that belonged to a multiplet. If multiplet formation is solely due to changes in event rates we would expect to see a constant daily percentage of events that belong to a multiplet. Daily percentages are plotted in Figure 4.10 and indicate that the percentage of events per day that belong to a multiplet varies throughout the study period rather than remaining constant. At the start of the study period percentages are low; ~15-20% of daily events belong to a multiplet during April 2010. There is then a rapid increase in percentage, during May and June 2010 there are ~60-80% of daily events belonging to a multiplet. This high percentage does not correspond to any increase in the onset of new multiplets (Figure 4.8). Percentages are low, ~15-20% (Figure 4.10) during July and August 2010 but then increase suddenly, but briefly, to ~60-80% at the beginning of September 2010. This
Figure 4.9. Three example multiplets, displayed as four randomly selected super-imposed waveforms from the multiplet. a) Multiplet A, began on the 1\textsuperscript{st} April 2010, events have average peak frequency of 4.2 Hz, b) Multiplet B, began on the 24\textsuperscript{th} August 2010, events have average peak frequency of 7.1 Hz c) Multiplet C, began on the 7\textsuperscript{th} June 2011, events have average peak frequency of 4.3 Hz.
spike in percentages corresponds to an onset of new multiplets (Figure 4.8). Percentages then decrease over the next four months, to a minimum of ~5 % in January 2011. During the onset of the eruptive period in March 2011, percentages increase (Figure 4.10), reaching a maximum of ~60 %, although event rates and new multiplet rates (Figure 4.8) do not start to increase until a few weeks later. The three event swarms in September 2011, November 2011 and February 2012 all have high percentages of events that belong to a multiplet (Figure 4.10). Percentages remain low during 2012. A seismic swarm occurs in April-May 2013, after the end of our study period for this analysis (see Chapter 3); however, we observe an increase in percentages in March 2013, just before the onset of this swarm, reaching a maximum of 93% on the final day of our study period.

Figure 4.10. Daily percentage of events that occur as part of a multiplet. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey.
4.5 DISCUSSION

4.5.1 Discussion of code performance

We compared the results of our peakmatch and graph-connectivity method to the equivalent results from the two-stage method of Petersen (2007) and Thelen et al. (2010). The code performed better than anticipated in terms of run time and memory usage and was able to cross-correlate the ~16,000 events in just over 1 hr, using the parameters we chose. Our code identified significantly more connected events than the two-stage method identified; we identified a total of 8340 events versus the 2366 identified via the two-stage method. Of the 2366 events identified via the two-stage method, 98% of these were also identified using peakmatch. We would expect our method to find more connected events as our method only required a 2-event minimum for a multiplet, whereas the two-stage method required a 4-event minimum; however, peakmatch identified 6123 events that belong to multiplets with a 4-event minimum, which is still considerably more than identified via the two-stage method. Another possible explanation for the difference in connected events identified could be due to the inclusion of multiplets that occur entirely within a 24 hr period, as these would not be identified in the two-stage method. Of the 6982 non-orphaned events (orphaned events were excluded as being a single event; by definition they occur entirely within a 24 hr period) only 103 events (1.5%) belonged to multiplets that occurred entirely with a single 24 hr period, therefore this is not a significant source of the difference between the methods in number of connected events. The two-stage method would only find multiplets if two-or-more events occurred on more than one day. Of the 6123 events in the peakmatch catalogue that contained 4 or more events (and could therefore be directly compared to the two-stage method) peakmatch identified 889
events (14.5%) that belonged to multiplets that would not have been identified using the two-stage method; (i.e. they contained fewer than two events per day for less than two days). It is not only the detection of entire multiplets that are missed that may account for the increase in connected events using the peakmatch method, but also the addition of single events from different days into existing multiplets. We suspect that an additional reason for the difference between the number of connected events between the two methods is a result of cropping the waveforms before cross-correlation, leading to improved correlation coefficients and therefore more events identified above the threshold.

To perform a full cross-correlation of all 217,101 events from the TESAND data set would require 23.6 billion operations. The post-process phase of peakmatch was able to perform an individual cross-correlation calculation in ~1 ms (after the FFTPRECACHE stage). Given this event pair calculation rate, cross-correlation of the entire 23.6 billion event pairs would take almost 273 days to complete, while using the fast-approximation stage allowed us to complete this in just over 13 hrs.

Due to the design of this program to solve a very specific large-volume data problem, there are a few features that could be considered limitations. Events must already be in an event-detected catalogue, the program cannot search continuous waveform data for multiplets. This program writes output to text files for further analysis by the user; it does not display graphical representations of the output data. Again, this is due to the nature of the design; we aimed to
write a program that could handle large amounts of data efficiently rather than re-create features in existing software (e.g., GISMO Reyes and West, 2011).

4.5.2 Patterns of multiplet activity at Telica

Multiplets occur in most volcanic data catalogues and the presence of multiplets alone is not sufficient to forecast eruptions (West, 2013). Analysis of temporal changes in multiplets can be used to infer changes in source processes or source locations of volcanic earthquakes, or changes in stress or fracturing conditions in the volcanic edifice. The presence of repeating events with similar waveforms can indicate a stable seismic source, both in terms of location and source-process (Geller and Mueller, 1980), and a stable stress regime (West, 2013). Multiplets that repeat over a long duration indicate that the source process must be both repeatable and non-destructive. At Telica, approximately 1000 events of the largest multiplet (of ~5000 events) have repetition times of less than five minutes, suggesting that the seismic source must be capable of creating the same waveform on a rapidly repeating timescale. The persistence of this same multiplet throughout the entire study period indicates that the source of this multiplet is stable and is not destroyed, and repeated activation of the same multiplet may indicate a cyclic energy flux in the degassing system.

Of the TESAND catalogue, over 78% of the ~51,000 connected events had peak frequencies below 5 Hz. Low-frequency (LF) seismicity; (i.e., events with peak frequencies below 5 Hz (Lahr et al., 1994)), is commonly associated with resonance of fluid filled cavities and can be due to transport of magmatic and/or hydrothermal fluids (Chouet and Matoza, 2013, and references
Sustained high degassing rates have been observed at Telica (Tenorio, 1993 onwards) and unsteady transportation of magmatic and/or hydrothermal fluids through shallow conduits and/or cracks could be a rapid, repeatable and non-destructive source process for the LF multiplets at Telica. Trigger mechanisms for LF multiplets at Telica must also be capable of generating repeatable LF seismicity with high repetition rates. For example, the choked flow model (Chouet et al., 1994; Morrissey and Chouet, 1997), where superheated gas flowing past a constriction in a crack is accelerated to supersonic speeds and creates a downstream shockwave; or the ‘pressure cooker’ model (Nakano et al., 2003; Waite et al., 2008), where resonance of a crack is triggered by period depressurisation of a fluid filled crack, both meet the criteria of having rapid repetition rates and non-destructive sources and are plausible triggers for LF multiplets at Telica.

If the observed LF multiplets are related to the degassing process at Telica then the onset of new multiplets, or the re-activation of pre-existing multiplets, may represent periods of increased degassing. LF multiplets were observed at Soufriere Hills Volcano, Montserrat before a change from a period of accelerating inflation to decelerating inflation and then ceased at the end of the deflation period; these multiplets are interpreted as being related to a depressurisation process resulting from periodic release of pressurised magmatic gas (Green and Neuberg, 2006). Swarms of repeating events were observed at Shishaldin Volcano, Alaska between 2001 and 2004 (Petersen, 2007). Similarly to Telica, these multiplets have very high repetition rates and some have life-spans across the entire four-year study period. Shishaldin is an analogous volcano to Telica; it is a basaltic-andesitic PRV that has a similar degassing regime.
to Telica and also exhibits highly variable rates of seismicity that do not correlate clearly with eruption periods (Petersen et al., 2006). Shishaldin has an extremely active hydrothermal system (Petersen and McNutt, 2007) and multiplet activity at Shishaldin is interpreted as choked flow of fluid in the hydrothermal system (Petersen, 2007). At Telica the cyclic pattern of seismicity rates may relate to a transition between open-system and closed-system degassing (see Chapter 3). Multi-parameter observations (e.g., temperature, SO$_2$ flow rate and ash analysis) of the 2011 eruption (Geirsson et al., 2013) suggest hydrothermal mineralisation and sealing of the hydrothermal system as the cause of the transition to closed-system degassing periods. The eruption period then represents transition back from closed-system to open-system degassing. Periods of high percentages of multiplets and rapid onsets of new multiplets (i.e., high degree of waveform correlation) occur during the seismic swarms in August-September 2010, September 2011, November 2011 and February 2012 and could relate to periods of open-system degassing. Likewise periods of low event rates, low multiplet percentages and the onset of only a few new multiplets (i.e., low degree of waveform correlation) may represent periods of closed-system degassing at Telica. Temperature and gas measurements surrounding the 2011 eruption support the open-system to closed-system transition with higher fumaroles temperatures and SO$_2$ flow rates observed during the proposed open-system periods and lower fumaroles temperatures and SO$_2$ flow rates observed during the proposed closed-system periods (Geirsson et al., 2013).
The remaining 22% of multiplets at Telica have peak frequencies above 5 Hz. While these events may represent a continuum of source processes, high-frequency (HF) seismicity could be an indication of brittle-failure events in response to stress changes (Roman and Cashman, 2006). Multiplet activity at Bezymianny, Russia, and at Mount St Helens, USA are interpreted as occurring at the edges of a magma conduit and related to increasing pressure forcing more gas into cracks surrounding the conduit and increasing stress in the conduit walls (Thelen et al., 2011). West (2013) interprets the lifespan of multiplets at Bezymianny, Russia, as an indication of the stability of the stress regime and precursory multiplet activity before explosions at Bezymianny between 2006 and 2010 is interpreted as a gradual stress increase in the volcano before eruption. Changing stress conditions cannot account for the long life-spans of some of the multiplets observed at Telica (>3 yrs), but some of the short lived multiplets could be interpreted as changes in stress conditions at Telica.

### 4.6 CONCLUSIONS

We developed a program ‘peakmatch’ to efficiently handle the cross-correlation of large seismic datasets. The program uses a fast-approximation stage to pre-select potential candidate pairs for full cross-correlation. We also developed a program ‘graph-connectivity’ to identify connected events within the final cross-correlation output. We tested our program against the widely accepted two-stage method of Petersen (2007) and Thelen et al. (2010) and find that our method identifies more connected events, but identifies a similar overall pattern of multiplet formation. We find that our method performs cross-correlation of large data catalogues
extremely quickly: a data set of 200,000 events would take ~231 days for full cross-correlation; our method was able to do this in ~ 13 hrs.

Analysis of over 200,000 events from the three-year deployment of the TESAND network identified over 51,000 connected events, of which there were ~9400 multiplets with two or more events. We observe that the main periods of onset of new multiplets occur during seismic swarms in August-September 2010, September 2011, November 2011 and February 2012. Variations in daily percentages of events that occur as part of a multiplet indicate that this increase in multiplet formation is not solely a consequence of higher daily event rates. We suggest that the onset of new multiplets in conjunction with high event rates and high percentages of daily events that belong to a multiplet, indicate periods of open-system degassing at Telica, and that periods of low new multiplet formation in conjunction with low event rates and low daily percentages of events that belong to a multiplet may indicate periods of closed-system degassing. Transitions between open-system and closed-system degassing are observed prior to eruptive episodes at Telica (see Chapters 2 and 3) and multiplet analysis may allow for future identification of periods of transition between degassing regimes.

4.7 DOWNLOADING THE SOURCE CODE

Source code is hosted by github and is available for free. Source code, complete program documentation, system requirements and usage instructions are given on these pages:
Source code is also uploaded as a supplemental file of this dissertation.

4.8 ACKNOWLEDGEMENTS

We thank the staff at INETER for the 1999-2000 data and for assistance and support during deployment of the TESAND network. The programs ‘peakmatch’ and ‘graph-connectivity’ were written by Simon Rodgers and this chapter would not have been possible without his help. This work was funded by National Science Foundation (NSF) grant EAR-0911366 to D. Roman and EAR-0911546 to P. LaFemina.
CHAPTER FIVE:

SEISMIC AND INFRASOUND OBSERVATIONS OF VULCANIAN EXPLOSIONS FROM THE 2011 ERUPTION OF TELICA VOLCANO, NICARAGUA.

ABSTRACT

The 2011 eruption of Telica Volcano, Nicaragua was characterised by a series of small vulcanian explosions over three months. A seismic network, including one infrasound sensor, was deployed on Telica during the eruption. In this study we analyse the hourly seismicity rates surrounding three large explosions in the eruptive period and find a precursory two-hour decrease in seismicity rates before each explosion. The infrasound signal associated with the two explosions that were recorded by the pressure sensor shows an initial low-amplitude signal, followed by a large N-wave (named for the resemblance of the waveform to the letter 'N') and sustained coda. These events are interpreted as an initial degassing phase that destabilised the pressurised magmatic and/or hydrothermal system and triggered the vent-opening explosion blast.
5.1 INTRODUCTION

Atmospheric pressure waves are generated at the vent by the rapidly expanding gas phase of an explosion. Infrasonic signatures have been observed at many volcanoes and can be generated by a wide variety of volcanic processes, from large impulsive explosions, to sustained rockfalls (Fee and Matoza, 2013). For example, infrasound signals have been observed in relation to degassing processes at Shishaldin Volcano, Alaska (Petersen and McNutt, 2007) and at Stromboli, Italy, low-amplitude infrasound signals have been linked to sustained bubble bursting (Ripepe et al., 1996). Vulcanian explosions at Augustine Volcano, Alaska, are observed acoustically as a sharp impulsive onset followed by a sustained coda (Petersen et al., 2006). Due to the wide variety of infrasonic signals generated at volcanoes, analysis of the infrasound signature of eruptions can lead to greater understanding of the processes occurring during eruptive activity.

Telica volcano, Nicaragua, is characterised by persistent degassing and frequent small (VEI 1-2) eruptions. In 2010 a seismic and GPS network (TESAND network) was installed on Telica, and a single Chaparral Physics Model 25V infrasound sensor was co-located with one of the broadband seismometers (TBCF – Figure 5.1), 0.2 km from the crater. In 2011 there was a three-month-long series of phreatic vulcanian explosions at Telica. The eruption began on the 7th March 2011 and the main phase of the eruption occurred from the 8th May 2011 to the 24th May 2011. Some of the most energetic explosions of the eruption period occurred at UTC 13:50 and UTC 19:50 on the 18th May 2011 (here labelled Explosions A and B), and at UTC 20:56 on the 21st May 2011 (Explosion C), all of which produced plumes of between 1.5 – 2 km above the
Figure 5.1. Location of Telica Volcano and seismic stations TBCF and TBTN: Inset map: Central America (right) and major volcanic centres of Nicaragua (left).
crater rim (Geirsson et al., 2013). Unfortunately due to station outages, only data from the 11th to the 15th May 2011 and from the 20th May 2011 onwards were recorded by the infrasound sensor. Therefore, of the large explosions, only the UTC 20:56 21st May 2011 explosion (Explosion C) was recorded at TBCF. In this study we present a preliminary analysis of infrasound data from one of the most energetic explosions (Explosion C) of this eruption and from one smaller explosion at UTC 22:34 on the 21st May 2011 (Explosion D). Additionally we present hourly seismicity rates with a chronology of explosions observed visually and seismically.

5.2 METHODS

5.2.1 Visual observations and seismic detection of explosions

Visual observations of explosions were documented by researchers from Pennsylvania State University during daylight hours (~ 8 am to 6 pm) from the 13th May 2011 to the 22nd May 2011 (H. Geirsson, pers. comm.), although some small explosions may not have been observed. Explosion quakes from station TBTN (Figure 5.1) were identified by eye in the continuous waveform data for the month of May (apart from during a station outage on the 16th May 2011). These seismic signals are identified by their emergent onset, cigar-shaped envelopes and broad frequency content (Figure 5.2).
Figure 5.2. Seismic waveform of explosion quake at UTC 16:21 on the 7th May 2011, from station TBTN. Waveform is filtered between 0.5 – 20 Hz.

5.2.2 Pressure sensor detection of explosions

Explosions were detected in the pressure data by visual inspection of the continuous pressure data and comparison with the seismic data. Due to station outages only explosions between 11th- 15th May and from the 20th May onwards were recorded on the pressure sensor. The high seismic activity at Telica, low acoustic impact of most of the explosions, and high wind noise made detection of signals from individual explosions difficult. Two explosions were selected for detailed analysis: firstly, one of the large explosions of the eruption period (UTC 20:56 21st May 2011, Explosion C) that produced plume heights 1.5 – 2 km above the crater, and secondly, a smaller explosion from the same day (UTC 22:34 21st May 2011, Explosion D).
5.3 RESULTS

The visually and seismically detected explosions were compared to hourly seismicity rates for low-frequency, high-frequency and mixed-frequency events from station TBTN (Figure 5.3) (for details on seismic event detections and event classifications see Chapter 3). There is little obvious correlation between hourly event rates and the timing of explosions over this time scale; however, we note that our catalogue of explosion times is incomplete. Hourly event rates for total seismicity were plotted for the 18th May 2011 and the 21st May 2011, when the three large explosions occurred (Explosions A, B, C, Figures 5.4 and 5.5). Event rates are highly variable, but Figures 5.4 and 5.5 suggest a reduction in event rates immediately before the large explosions: On the 21st May, between UTC 16:00 and UTC 17:00 there were 28 events recorded at TBTN, and only 3-4 events per hour recorded during 19:00-21:00, the two hours before Explosion C (Figure 5.5). The decrease in event rate before the two 18th May 2011 explosions (Explosions A and B) is less noticeable. Hourly event rates drop from 17 events to 11 events per hour for the two hours preceding the UTC 13:50 explosion (Explosion A) and from 12 events to 7 events in the two hours preceding the UTC 19:50 explosion (Explosion B) (Figure 5.4). However, we note that there are many more instances where a drop in hourly event rate is not followed by an explosion and that our data set of three explosions is not conclusive.
Figure 5.3. TOP: observed explosion events (circles) and seismically detected explosion events (inverted triangles) from the 7th May 2011 to the 25th May 2011. BOTTOM: hourly event rates for low-frequency (LF), high-frequency (HF) and mixed-frequency (MF) events.
Figure 5.4. Hourly event rates for the 18th May 2011. Explosion A at UTC 13:50 and Explosion B at UTC 19:50 are marked by arrows.

Figure 5.5. Hourly event rates for the 21st May 2011. Explosion C at UTC 20:56 and Explosion D at UTC 22:34 are marked by arrows. N.B. Explosion D at UTC 22:34 is not one of the three largest explosions.
A large explosion occurred on the 21st May 2011 at UTC 20:56 (Figure 5.6, Explosion C) and was recorded on the infrasound sensor. The acoustic signal consists of an initial spike with dominant frequency below 1 Hz, followed 10s later by an N-wave with broadband energy up to 5 Hz and a dominant frequency ~ 0.2 Hz. The seismic signal associated with this explosion starts approximately five seconds after the initial small acoustic signal. The seismic waveform has an emergent onset, a cigar-shaped envelope, and a dominant frequency of ~ 20 Hz.

An explosion with a smaller plume height occurred at UTC 22:34 (Figure 5.7, Explosion D). The seismic signal of this event has four distinct pulses, the first three of which have seismic energy < 2 Hz and the final has energy ~ 20 Hz. The acoustic signal associated with the first three pulses is low-amplitude, < 2 Hz signal that continues for ~ 50 seconds. Immediately after the third seismic pulse there is a small N-wave signal in the acoustic signal, with dominant frequency of 1 Hz, this is followed 10s later by a large N-wave with broadband energy up to ~ 5 Hz and a dominant frequency of 0.2 Hz. The final seismic pulse starts approximately five seconds after the initial small N-wave, has an emergent onset and a cigar-shaped envelope. Visual observation of the onset of the ash plume at UTC 22:34 matches the timing of the large acoustic N-wave signal. Note there is an order of magnitude difference between the seismic and the pressure amplitudes.
Figure 5.6. Waveform and spectrograms of acoustic (top) and seismic (bottom) signals of Explosion C at UTC 20:56 on the 21\textsuperscript{st} May 2011. Spectrograms produced using a window size of 2s, overlap of 1s and FFT size of 256. Instrument response information can be found in Appendix B. N.B. Acoustic and seismic waveforms are not offset.
Figure 5.7. Waveform and spectrograms of acoustic (top) and seismic (bottom) signals of Explosion D at UTC 22:34 on the 21st May 2011. Spectrograms produced using a window size of 2s, overlap of 1s and FFT size of 256. Instrument response information can be found in Appendix B. N.B. Acoustic and seismic waveforms are not offset.
5.4 DISCUSSION

Documented hourly seismicity rates before three of the largest explosions during the May 2011 eruption suggest that there is a brief, two-hour long, reduction in event rate before the three explosions. Short-term decreases in seismicity have been observed prior to other volcanic eruptions: For example, a ten-hour period with no LF events was observed before the March 1993 eruption of Galeras (Fisher et al., 1994) and a 33-hour period of seismic quiescence was observed at Mount Pinatubo in the pre-explosive phase of the 1991 eruption (Harlow et al., 1996). At Soufrière Hills Volcano, Montserrat, cyclic decreases in SO$_2$ emissions preceded explosions in May-June 1999 and were attributed to changes in permeability in the conduit and dome, either resulting from rheological changes in cooling magma, or from the precipitation of minerals in gas pathways (Edmonds et al., 2003). During the 2009 eruption of Redoubt there was ~ 30 seconds of tremor quiescence immediately before some of the explosions (Hotovec et al., 2013). This was interpreted as being due to extremely high stress rates from conduit pressurisation that caused a transition from stick-slip events to aseismic sliding (Dmitrieva et al., 2013). During the eruption period at Telica, LF and MF seismicity dominates the seismic catalogue (Figure 5.3). LF seismicity is frequently associated with resonance of a fluid filled cavity (Chouet and Matoza, 2013, and references therein) and the transport of magmatic and/or hydrothermal fluids is a plausible source of LF seismicity at Telica given the high levels of degassing (Tenorio, 1993 onwards). Analysis of multi-year seismic trends at Telica suggests a cyclic transition between open-system and closed-system degassing before eruptions at Telica (Rodgers et al., 2013, and Chapter 3). If seismicity at Telica is related to fluid flow, the short-
term reduction in event rates before the explosions (Figure 5.4 and 5.5) could be an indication of sealing of the degassing pathways immediately prior to explosions.

The acoustic signal of Vulcanian explosions is often observed as an initial sharp N-wave followed by sustained infrasonic jetting or tremor (Fee and Matoza, 2013). For example, some of the explosions during the 2006 eruption of Augustine, Alaska had an initial impulsive broadband (up to 5 Hz) N-wave, followed by a low-amplitude, lower-frequency coda (Petersen et al., 2006). This initial impulsive N-wave was interpreted as a sudden opening of the vent and the sustained coda related to the sustained generation of the ash-cloud. Emergent acoustic signals were also observed during this eruption (Petersen et al., 2006) and were interpreted as sustained release of pyroclasts and gas, without the vent opening phase. Infrasound observations are also associated with non-eruptive degassing activity at Shishaldin, Alaska (Petersen and McNutt, 2007) where discrete gas puffs were observed in conjunction with an impulsive broadband N-wave followed by a low-frequency coda in the acoustic signal. At Telica, the observation of a low-amplitude infrasound signal before the main N-wave could indicate a degassing event prior to the main vent opening explosion phase. If the seismic and acoustic signals are generated at the same time, due to the difference in travel-time of seismic waves vs. acoustic waves, the seismic waveform should be observed first. However, observations at Telica from the 21st May 2011 UTC 20:56 explosion (Explosion C) (Figure 5.6) suggest that the seismic and acoustic waveforms, at least for the first acoustic arrivals, are not coupled in this way. The two distinct phases of the seismo-acoustic signal suggest that there is an initial gas-release event that is too small to be detected seismically. The three LF events co-incident with the low-
amplitude infrasound signal before the 21st May 2011 UTC 22:34 explosion (Explosion D) (Figure
5.7) suggests that there was a series of small degassing events before the main ash-producing
explosions initiated. We interpret the seismo-acoustic signals at Telica as initial degassing
events that destabilised the pressured magmatic gas/hydrothermal system, leading to the main
ash-producing explosion.

5.5 CONCLUSIONS
Telica erupted in May 2011 with a series of small Vulcanian explosions. Hourly seismicity rates
before three of the largest explosions in this eruption show a decreased rate of seismicity for a
two-hour period before these explosions. We interpret these signals as sealing of the degassing
processes before the explosions. Acoustic observations of two explosions on the 21st May 2011
suggest an initial low-amplitude degassing phase occurred before the main vent-opening
explosion.
6.1 CONCLUSIONS OF THIS DISSERTATION

Analyses of large seismic data catalogues using relatively straightforward metrics, e.g. event rates, variations in spectral content and event classifications, demonstrate simple, yet effective ways of elucidating changes in volcanic processes. Seismicity at PRVs is highly variable and shows little clear correlation with eruptive activity. To investigate the patterns of seismicity at a PRV we analysed data from two VEI 2 eruptions at Telica Volcano, Nicaragua. We first analysed single-station short-period seismic data from a period surrounding the 1999 eruption of Telica. In 2009-2010 we installed a broadband seismic and continuous GPS network on Telica and we analysed the seismicity from the entire three-year initial deployment of this network, including a period surrounding the 2011 eruption. Event rates at Telica are high and variable, and are dominated by low-frequency (LF) seismicity. Between 2009 and 2013 over 400,000 events were detected at the summit station at Telica, of which approximately 77% had peak frequencies below 5 Hz. The average daily event rate of approximately 300 events per day varied from a minimum of 5 events per day to a maximum of 1400 events per day.
From our analysis of the seismicity surrounding the two most recent VEI 2 eruptions at Telica (1999 and 2011), we observed decreases in seismicity several months before the eruptions and increased seismicity after the eruptions. In 1999, approximately three months before the eruption, we observed a decrease in LF events which was immediately followed by a high-frequency HF swarm and then relative seismic quiescence before the eruption. A similar pattern occurred between two of the explosive phases of the 1999 eruption, where LF events decreased, then were followed by an HF swarm and a series of explosions. Seismicity was then low for a two-month period before the final large explosions of this eruptive episode and then increased in the period following the eruptive episode. Prior to the 2011 eruption, an LF and an HF swarm preceded a decrease in seismicity six-months before the eruption and event rates reached a minimum just after the eruption onset. Seismicity then increased during and following the eruption. A repeated pattern of seismic swarms and seismic shut-off was then observed over the following two years (up to the time of writing). Seismicity at Telica is generally dominated by LF events, but we observe variations in spectral content during these repeated patterns of seismicity, with a progressive loss of LF events during the decreases in seismicity and the re-appearance of events with a broad range of frequencies during the seismic swarms. Analysis of multiplet activity indicates the presence of repeating families of events (multiplets) with a wide variety of life-spans. The onset of new multiplets often corresponds to periods of high event rates and high percentages of daily events that belong to a multiplet.
We interpret our seismic observations as related to a cyclic transition between open-system and closed-system degassing. PRVs such as Telica do not exhibit clear ‘background’ or ‘unrest’ phases, and observations on a much longer time-scale are necessary to assess what constitutes ‘normal’ behaviour at Telica. However, we suggest that open-system degassing behaviour is common at Telica and is characterised by high event rates, a broad range of frequency contents and high degrees of waveform correlation. Transitions to closed-system degassing are indicated seismically by low event rates, higher frequency content of events and low degrees of waveform correlation. The transition to closed-system degassing may be due to sealing of the hydrothermal system due to hydrothermal mineralisation, or may be due to magma withdrawal from the conduit. In this model the phreatic eruption then represents the transition from closed-system degassing back to open-system degassing. The interpretation that the onset of phreatic vulcanian eruptive periods occurs during closed-system degassing periods has clear implications for eruption forecasting and volcano monitoring; however, not all periods of closed-system degassing culminate in eruptions. Therefore the processes controlling the degassing processes must be capable of transitioning from closed-system to open-system degassing without a significant eruption.

6.2 FUTURE WORK

Large seismic data catalogues present a challenge for volcano seismology research and identifying pertinent information within hundreds of thousands of events can be an overwhelming task. Many advanced seismic analysis techniques, such as moment-tensor analysis (Kumagai et al., 2005), double difference re-location (Waldhauser and Ellsworth, 2000),
or stress analysis from fault plane solutions (Roman and Cashman, 2006), require pre-selection of suitable types of earthquakes; for example, volcano-tectonic earthquakes (VTs) are necessary for stress analysis techniques, and moment-tensor analysis is generally performed on low-frequency events. In a data catalogue of hundreds of thousands of events, selecting suitable events for further analysis is a necessary first step and as such a robust classification scheme is necessary to identify those events suitable for specific advanced analyses.

In our classification scheme we identify LF and HF events, but also an additional third class, the MF events. Our justification for doing this was to ensure the LF and HF classes were not influenced by events with slightly varying spectral properties, i.e. with only a two class system a slight variation in dominant spectral properties could shift an event from the LF class to the HF class, or vice versa. By introducing a middle MF class we have more confidence that our LF and HF classes represent events with true LF and HF content. However, this MF ‘collector’ class will contain LF events with some HF energy and also contain some VT events that have a significant LF coda (Lahr et al., 1994). Detailed study and re-classification of events in this MF class will improve our analysis of seismicity patterns at Telica and allow for a more complete identification of event types, for example, if VT swarms are hidden within the MF class, then potentially these seismicity patterns are being missed in our classification scheme.

Our model of a transition from open-system to closed-system degassing may only pertain to phreatic non-juvenile eruptions and precursory seismicity for larger magmatic eruptions may be entirely different. Ongoing seismic, deformation, infrasound, gas and thermal monitoring at
volcanoes such as Telica will improve our understanding of the seismic and magmatic processes occurring at PRVs prior to and during eruptive activity. A recently installed gas sensor, and field campaigns with new gas monitoring methods, e.g. UV cameras (Mori and Burton, 2006), will provide quantitative results on the degassing processes occurring at Telica and allow us to assess the open-system to closed-system degassing hypothesis.
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APPENDIX A:
ADDITIONAL FIGURES FROM CHAPTER 3

The following figures are supplemental figures from Chapter 3. Figure A1 shows a series of photographs of Telica’s active crater. These photos were taken from the same location during maintenance visits to the TESAND network from November 2009 until March 2013. Incandescence is visible in many of the photographs and the location of incandescent areas remains within the inner crater, but changes slightly over the three-and-a-half years. The photographs from May 2011 were taken during the 2011 eruption and show the inner crater area has deepened. A subsequent incandescent circle was observed in the inner crater in August 2011 and incandescence persisted in this area for the remainder of the observation period. Figures A2 and A3 show the same daily event rates data from station TBTN, as plotted in figure 3.8 (Chapter 3), however figure A2 shows the data plotted as cumulative event rates and figure A3 shows the data plotted by year. Figures A4, A5 and A6 show the dominant frequency, the band-ratio and the amplitude of every event from each station in the TESAND network between April 2010 and March 2013. Figures A4 and A5 show that similar frequency content is observed across all stations, apart from at station TBHS where higher frequency content is observed. Figure A6 indicates similar temporal changes in amplitude are observed at all stations. Table A1 is a list of eruptions at Telica from 1527 onwards, this list is compiled from the Global Volcanism Program (Seibert and Simkin (2002)).
b)

June 2010

January 2011
May 2011
August 2011
November 2011
February 2012
July 2012
September 2012
Figure A1  Crater floor photographs from TESAND maintenance visits from November 2009 to March 2013. a) November 2009 and March 2010; b) June 2010 and January 2011; c) May 2011; d) August 2011; e) November 2011; f) February 2012; g) July 2012; h) September 2012; i) March 2013. Where possible the zoomed photo is indicated on the larger photo of the whole crater floor. All photos taken by M. Rodgers and H. Geirsson.
Figure A2. Cumulative daily event rates from November 2009 until May 2013 from station TBTN.
Figure A3. Total daily seismic event counts (black bars) and RSAM (black circles) from 2010 (top), 2011 (middle) and 2012 (bottom). The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey.
Figure A4. Dominant frequency of all events at stations a) TBCA, TBCF and TBHS; b) TBHY, TBMR and TBTN. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey. Periods with no data are indicated by asterisks under the time-axis.
Figure A5. Frequency band-ratio of all events at stations **a)** TBCA, TBCF and TBHS; **b)** TBHY, TBMR and TBTN. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey. Periods with no data are indicated by asterisks under the time-axis.
Figure A6. Amplitude of all events at stations a) TBCA, TBCF and TBHS; b) TBHY, TBMR and TBTN. The eruption period is marked by grey shaded boxes, the more energetic phase of the eruption in dark grey. Periods with no data are indicated by asterisks under the time-axis.
Table A1: Table of documented eruptions at Telica

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<td>1948 (January)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1948 (June)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1951</td>
<td>2</td>
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<tr>
<td>1962</td>
<td>1</td>
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<tr>
<td>1965</td>
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<td></td>
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<tr>
<td>1966</td>
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</tr>
<tr>
<td>1969</td>
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<tr>
<td>1975</td>
<td>0</td>
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</tr>
<tr>
<td>1976</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1981 (February)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1981 (November)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1987</td>
<td>1</td>
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<td>1994</td>
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<tr>
<td>1999</td>
<td>2</td>
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<tr>
<td>2001</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>0</td>
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</tr>
<tr>
<td>2004 (March)</td>
<td>1</td>
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</tr>
<tr>
<td>2004 (November)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2007 (June)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2007 (October)</td>
<td>1</td>
<td>?</td>
</tr>
<tr>
<td>2008</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX B:

INSTRUMENT RESPONSE FILES

1. T6780/DM24 (TBCF/TBCA)

2. Chaparral 25V (TBCF)

3. T6776/C289 (TBHS)

4. T6775/C290 (TBHY)

5. T6779/C291 (TBMR)

6. T6777/C292 (TBTN & TBCA)

7. T6B87/C1344 (TBTN & TBCA)
### Table B1: Dates of installation of instruments at TESAND stations

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Station</th>
<th>Install date</th>
<th>Removal date</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6780/DM24</td>
<td>TBCA</td>
<td>14\textsuperscript{th} March 2010</td>
<td>22\textsuperscript{nd} June 2010</td>
</tr>
<tr>
<td>T6780/DM24</td>
<td>TBCF</td>
<td>26\textsuperscript{th} June 2010</td>
<td>Still running</td>
</tr>
<tr>
<td>T6776/C289</td>
<td>TBHS</td>
<td>15\textsuperscript{th} March 2010</td>
<td>Still running</td>
</tr>
<tr>
<td>T6775/C290</td>
<td>TBHY</td>
<td>11\textsuperscript{th} March 2010</td>
<td>Still running</td>
</tr>
<tr>
<td>T6779/C291</td>
<td>TBMR</td>
<td>14\textsuperscript{th} March 2010</td>
<td>Still running</td>
</tr>
<tr>
<td>T6777/C289</td>
<td>TBTN</td>
<td>24\textsuperscript{th} November 2009</td>
<td>26\textsuperscript{th} June 2010</td>
</tr>
<tr>
<td>T6777/C289</td>
<td>TBCA</td>
<td>1\textsuperscript{st} February 2011</td>
<td>15\textsuperscript{th} May 2011</td>
</tr>
<tr>
<td>T6777/C289</td>
<td>TBTN</td>
<td>16\textsuperscript{th} May 2011</td>
<td>Still running</td>
</tr>
<tr>
<td>T6B87/C1344</td>
<td>TBTN</td>
<td>26\textsuperscript{th} June 2010</td>
<td>16\textsuperscript{th} May 2011</td>
</tr>
<tr>
<td>T6B87/C1344</td>
<td>TBCA</td>
<td>21\textsuperscript{st} November 2011</td>
<td>17\textsuperscript{th} July 2012</td>
</tr>
</tbody>
</table>
1. T6780/DM24

CMG-6T CALIBRATION SHEET T6780

WORKS ORDER: 3926 DATE: 25/10/07
SERIAL NUMBER: T6780 TESTED BY: S. Goddard

<table>
<thead>
<tr>
<th>Velocity Output</th>
<th>Mass Position Output (Acceleration output)</th>
<th>Feedback Coil Constant Amp/m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td>V/m/s (Differential)</td>
<td>V/m/s²</td>
<td></td>
</tr>
</tbody>
</table>

VERTICAL 2 x 1201 15.7 0.004752

NORTH/SOUTH 2 x 1201 15.3 0.004646

EAST/WEST 2 x 1200 15.0 0.004536

Power Consumption: 22mA @ +12V input
Calibration Resistor: 51000

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.
POLES AND ZEROS TABLE

WORKS ORDER NUMBER: 3926

SENSOR SERIAL NO: T6780

Velocity response output, Vertical Sensor:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^3 ± j -23.56 x 10^3</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 ± j 135.392</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: A = 585.8 x 10^6


Velocity response output, Horizontal Sensors:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^3 ± j -23.56 x 10^3</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 ± j 135.392</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: A = 585.8 x 10^6


NOTE: The above poles and zeros apply to the vertical and the horizontal sensors and are given in units of Hz. To convert to Radian/sec multiply each pole or zero with 2π. The normalizing factor A should also be recalculated.
DM24 CALIBRATION

WORKS ORDER: 3926                  DIGITISER SERIAL NUMBER: B726

SYSTEM ID: 3926                      CPLD: A0.E1
UNIT ID: B726                         BOOTLOADER: BOOT1027.IMG
OUTPUT DATA FORMAT: GCF              DSP SOFTWARE: DSP48CH1055.BIN
BAUD RATE: 38400                     SYSTEM: ARMFWDM103b50.IMG

VELOCITY CHANNELS

Channel: B726Z2  Vertical  3.212 µV/Count
         B726N2  North/South  3.201 µV/Count
         B726E2  East/West   3.201 µV/Count
         B726Z3  Vertical    3.215 µV/Count
         B726N3  North/South 3.216 µV/Count
         B726E3  East/West   3.224 µV/Count

MASS POSITION CHANNELS

Sample Rate:  4 samples/sec (Default)

Channel: B726M8  Vertical  292.94 µV/Count
          B726M9  North/South  293.99 µV/Count
          B726MA  East/West   293.00 µV/Count

Sample Rate:  1 samples/sec

Channel: B726M8  Vertical  1.144 µV/Count
          B726M9  North/South  1.148 µV/Count
          B726MA  East/West   1.145 µV/Count

CAL SIGNAL MONITOR

B726X2 / B726C2  3.219 µV/Count

GPS RECEIVER

PWM: 8000 Counts
At Temperature Reading: 23°C
### POWER CONSUMPTION

<table>
<thead>
<tr>
<th>Component</th>
<th>Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digitiser Power</td>
<td>80mA @ 12v</td>
</tr>
<tr>
<td>GPS Power</td>
<td>28mA @ 12v</td>
</tr>
</tbody>
</table>

### AUXILIARY CHANNELS

**Sample Rate:** 4 samples/sec (Default)

<table>
<thead>
<tr>
<th>Channel</th>
<th>µV/Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>B726MB</td>
<td>292.83</td>
</tr>
<tr>
<td>B726MC</td>
<td>294.26</td>
</tr>
<tr>
<td>B726MD</td>
<td>292.05</td>
</tr>
<tr>
<td>B726ME</td>
<td>293.88</td>
</tr>
<tr>
<td>B726MF</td>
<td>292.40</td>
</tr>
</tbody>
</table>

**Sample Rate:** 1 samples/sec

<table>
<thead>
<tr>
<th>Channel</th>
<th>µV/Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>B726MB</td>
<td>1.144</td>
</tr>
<tr>
<td>B726MC</td>
<td>1.149</td>
</tr>
<tr>
<td>B726MD</td>
<td>1.141</td>
</tr>
<tr>
<td>B726ME</td>
<td>1.148</td>
</tr>
<tr>
<td>B726MF</td>
<td>1.142</td>
</tr>
</tbody>
</table>
2. Chaparral 25V

Calibration Report

For Serial Number: 071954
Model 25V Operating voltage 12v
Calibrator used: s/n 3

Switch in: High Gain
Cal value: 0.491 V/Pa
Cal value: 0.460 V/Pa
Cal value: V/Pa
Spike value: 1.06 V
Calculated LF 3dB Point: 0.052 Hz
At Barometric Pressure: 990.85 mBar
at Freq: 1.02 Hz
at Freq: 0.105 Hz
at Freq: Hz

Switch in: Low Gain
Cal value: 0.0488 V/Pa
Cal value: 0.0482 V/Pa
Cal value: V/Pa
Spike value: 0.11 V
Calculated LF 3dB Point: 0.034 Hz
At Barometric Pressure: 990.85 mBar
at Freq: 1.02 Hz
at Freq: 0.106 Hz
at Freq: Hz
### CMG-6T CALIBRATION SHEET T6776

**WORKS ORDER:** 3926  
**DATE:** 25/10/07  
**SERIAL NUMBER:** T6776  
**TESTED BY:** S. Goddard

<table>
<thead>
<tr>
<th></th>
<th>Velocity Output V/m/s (Differential)</th>
<th>Mass Position Output (Acceleration output) V/m/s²</th>
<th>Feedback Coil Constant Amp/m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VERTICAL</strong></td>
<td>2 x 1201</td>
<td>15.5</td>
<td>0.004700</td>
</tr>
<tr>
<td><strong>NORTH/SOUTH</strong></td>
<td>2 x 1194</td>
<td>15.2</td>
<td>0.004607</td>
</tr>
<tr>
<td><strong>EAST/WEST</strong></td>
<td>2 x 1206</td>
<td>15.6</td>
<td>0.004741</td>
</tr>
</tbody>
</table>

**Power Consumption:** 22mA @ +12V input  
**Calibration Resistor:** 51000

**NOTE:** A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.
POLES AND ZEROS TABLE

WORKS ORDER NUMBER: 3926

SENSOR SERIAL NO: T6776

Velocity response output, Vertical Sensor:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS HZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^{-3} ± j -23.56 x 10^{-3}</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 ± j 135.392</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: A = $585.8 \times 10^6$


Velocity response output, Horizontal Sensors:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^{-3} ± j -23.56 x 10^{-3}</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 ± j 135.392</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: A = $585.8 \times 10^6$


**NOTE:** The above poles and zeros apply to the vertical and the horizontal sensors and are given in units of Hz. To convert to Radian/sec multiply each pole or zero with $2\pi$. The normalizing factor A should also be recalculated.
CD24 CALIBRATION

WORKS ORDER: 3926
DIGITISER SERIAL NUMBER: C289
SENSOR SERIAL NUMBER: T6776
SYSTEM ID: W3926
UNIT ID: 6776
OUTPUT DATA FORMAT: GCF
SOFTWARE: UPPERN_V278
BAUD RATE: 19200

VELOCITY CHANNELS

Channel: 6776Z2 Vertical 0.958 µV/Count 398.731E-12 M/S/Count
6776N2 North/South 0.958 µV/Count 400.997E-12 M/S/Count
6776E2 East/West 0.960 µV/Count 398.200E-12 M/S/Count

MASS POSITION CHANNELS

Sample Rate: 1 samples/sec

Channel: 6776M8 Vertical 0.58 µV/Count 37.712E-9 M/S²/Count
6776M9 North/South 0.58 µV/Count 38.347E-9 M/S²/Count
6776MA East/West 0.59 µV/Count 37.507E-9 M/S²/Count

CAL SIGNAL MONITOR

6776MB 0.583 µV/Count

GPS RECEIVER

PWM: 525000 Counts
At Temperature Reading: 23°C

POWER CONSUMPTION

Digitiser Power Consumption 54mA @ 12v
### CMG-6T CALIBRATION SHEET T6775

**WORKS ORDER:** 3926  
**DATE:** 25/10/07  
**SERIAL NUMBER:** T6775  
**TESTED BY:** S. Goddard

<table>
<thead>
<tr>
<th></th>
<th>Velocity Output</th>
<th>Mass Position Output</th>
<th>Feedback Coil Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V/m/s (Differential)</td>
<td>(Acceleration output)</td>
<td>Amp/m/s²</td>
</tr>
<tr>
<td>VERTICAL</td>
<td>2 x 1196</td>
<td>15.9</td>
<td>0.004819</td>
</tr>
<tr>
<td>NORTH/SOUTH H</td>
<td>2 x 1206</td>
<td>15.4</td>
<td>0.004666</td>
</tr>
<tr>
<td>EAST/WEST</td>
<td>2 x 1194</td>
<td>14.7</td>
<td>0.004443</td>
</tr>
</tbody>
</table>

**Power Consumption:** 22mA @ +12V input  
**Calibration Resistor:** 51000

**NOTE:** A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.
**POLES AND ZEROS TABLE**

**WORKS ORDER NUMBER: 3926**

**SENSOR SERIAL NO: T6775**

Velocity response output, Vertical Sensor:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^{-3} ± j -23.56 x 10^{-3}</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 ± j 135.392</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td>0</td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: \( A = 585.8 \times 10^6 \)


Velocity response output, Horizontal Sensors:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^{-3} ± j -23.56 x 10^{-3}</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 ± j 135.392</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td>0</td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: \( A = 585.8 \times 10^6 \)


**NOTE:** The above poles and zeros apply to the vertical and the horizontal sensors and are given in units of Hz. To convert to Radian/sec multiply each pole or zero with \( 2\pi \). The normalizing factor \( A \) should also be recalculated.
CD24 CALIBRATION

WORKS ORDER: 3926
DIGITISER SERIAL NUMBER: C290
SENSOR SERIAL NUMBER: T6775
SYSTEM ID: W3926
UNIT ID: 6775
OUTPUT DATA FORMAT: GCF
SOFTWARE: UPPERN_V278
BAUD RATE: 19200

VELOCITY CHANNELS

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>Amplification</th>
<th>Velocity</th>
<th>Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>6775Z2</td>
<td>Vertical</td>
<td>0.959 µV/Count</td>
<td>400.747E-12 M/S/Count</td>
<td></td>
</tr>
<tr>
<td>6775N2</td>
<td>North/South</td>
<td>0.958 µV/Count</td>
<td>397.052E-12 M/S/Count</td>
<td></td>
</tr>
<tr>
<td>6775E2</td>
<td>East/West</td>
<td>0.957 µV/Count</td>
<td>400.888E-12 M/S/Count</td>
<td></td>
</tr>
</tbody>
</table>

MASS POSITION CHANNELS

Sample Rate: 1 samples/sec

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>Amplification</th>
<th>Velocity</th>
<th>Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>6775M8</td>
<td>Vertical</td>
<td>0.58 µV/Count</td>
<td>36.636E-9 M/S²/Count</td>
<td></td>
</tr>
<tr>
<td>6775M9</td>
<td>North/South</td>
<td>0.58 µV/Count</td>
<td>37.975E-9 M/S²/Count</td>
<td></td>
</tr>
<tr>
<td>6775MA</td>
<td>East/West</td>
<td>0.59 µV/Count</td>
<td>39.837E-9 M/S²/Count</td>
<td></td>
</tr>
</tbody>
</table>

CAL SIGNAL MONITOR

<table>
<thead>
<tr>
<th>Channel</th>
<th>Amplification</th>
</tr>
</thead>
<tbody>
<tr>
<td>6775MB</td>
<td>0.585 µV/Count</td>
</tr>
</tbody>
</table>

GPS RECEIVER

PWM: 525000 Counts
At Temperature Reading: 23°C

POWER CONSUMPTION

Digitiser Power Consumption: 54mA @ 12v
5. T6779/C291

CMG-6T CALIBRATION SHEET T6779

WORKS ORDER: 3926  DATE:  25/10/07
SERIAL NUMBER: T6779  TESTED BY: S. Goddard

<table>
<thead>
<tr>
<th></th>
<th>Velocity Output</th>
<th>Mass Position Output</th>
<th>Feedback Coil Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V/m/s (Differential)</td>
<td>V/m/s² (Acceleration output)</td>
<td>Amp/m/s²</td>
</tr>
<tr>
<td>VERTICAL</td>
<td>2 x 1195</td>
<td>15.8</td>
<td>0.004803</td>
</tr>
<tr>
<td>NORTH/SOUTH</td>
<td>2 x 1200</td>
<td>14.9</td>
<td>0.004502</td>
</tr>
<tr>
<td>EAST/WEST</td>
<td>2 x 1207</td>
<td>14.9</td>
<td>0.004530</td>
</tr>
</tbody>
</table>

Power Consumption: 22mA @ +12V input
Calibration Resistor: 51000

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.
**POLES AND ZEROS TABLE**

**WORKS ORDER NUMBER: 3926**

**SENSOR SERIAL NO: T6779**

Velocity response output, Vertical Sensor:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS HZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-23.56 \times 10^3 \pm j \cdot 23.56 \times 10^3$</td>
<td>0</td>
</tr>
<tr>
<td>$-62.3816 \pm j \cdot 135.392$</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: $A = 585.8 \times 10^6$


Velocity response output, Horizontal Sensors:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-23.56 \times 10^3 \pm j \cdot 23.56 \times 10^3$</td>
<td>0</td>
</tr>
<tr>
<td>$-62.3816 \pm j \cdot 135.392$</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: $A = 585.8 \times 10^6$


**NOTE:** The above poles and zeros apply to the vertical and the horizontal sensors and are given in units of Hz. To convert to Radian/sec multiply each pole or zero with $2\pi$. The normalizing factor $A$ should also be recalculated.
CD24 CALIBRATION

WORKS ORDER: 3926
DIGITISER SERIAL NUMBER: C291
SENSOR SERIAL NUMBER: T6779
SYSTEM ID: W3926
UNIT ID: 6779
OUTPUT DATA FORMAT: GCF
SOFTWARE: UPPERN_V278
BAUD RATE: 19200

VELOCITY CHANNELS

Channel: 6779Z2 Vertical 0.962 µV/Count 402.354E-12 M/S/Count
6779N2 North/South 0.957 µV/Count 398.944E-12 M/S/Count
6779E2 East/West 0.960 µV/Count 397.558E-12 M/S/Count

MASS POSITION CHANNELS

Sample Rate: 1 samples/sec
Channel: 6779M8 Vertical 0.59 µV/Count 37.061E-9 M/S²/Count
6779M9 North/South 0.59 µV/Count 39.414E-9 M/S²/Count
6779MA East/West 0.59 µV/Count 39.406E-9 M/S²/Count

CAL SIGNAL MONITOR

6779MB 0.587 µV/Count

GPS RECEIVER

PWM: 525000 Counts
At Temperature Reading: 23°C

POWER CONSUMPTION

Digitiser Power Consumption 54mA @ 12v
6. T6777/C292

CMG-6T CALIBRATION SHEET T6777

<table>
<thead>
<tr>
<th>Works Order:</th>
<th>3926</th>
<th>Date:</th>
<th>25/10/07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial Number:</td>
<td>T6777</td>
<td>Tested By:</td>
<td>S. Goddard</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>velocity Output V/m/s</th>
<th>Mass Position Output (Acceleration output) V/m/s²</th>
<th>Feedback Coil Constant Amp/m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>2 x 1198</td>
<td>15.7</td>
</tr>
<tr>
<td>North/South</td>
<td>2 x 1201</td>
<td>15.1</td>
</tr>
<tr>
<td>East/West</td>
<td>2 x 1181</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Power Consumption: 22mA @ +12V input
Calibration Resistor: 51000

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.
POLES AND ZEROS TABLE

WORKS ORDER NUMBER: 3926

SENSOR SERIAL NO: T6777

Velocity response output, Vertical Sensor:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS HZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^{-3} ± j -23.56 x 10^{-3}</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 ± j 135.392</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: $A = 585.8 \times 10^6$


Velocity response output, Horizontal Sensors:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^{-3} ± j -23.56 x 10^{-3}</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 ± j 135.392</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td></td>
</tr>
<tr>
<td>-75</td>
<td></td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: $A = 585.8 \times 10^6$


**NOTE:** The above poles and zeros apply to the vertical and the horizontal sensors and are given in units of Hz. To convert to Radian/sec multiply each pole or zero with $2\pi f$. The normalizing factor $A$ should also be recalculated.
**CD24 CALIBRATION**

**WORKS ORDER:** 3926  
**DIGITISER SERIAL NUMBER:** C292  
**SENSOR SERIAL NUMBER:** T6777  
**SOFTWARE:** UPPERN_V278

**SYSTEM ID:** W3926  
**UNIT ID:** 6777  
**OUTPUT DATA FORMAT:** GCF  
**BAUD RATE:** 19200

### VELOCITY CHANNELS

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>µV/Count</th>
<th>M/S/Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>6777Z2</td>
<td>Vertical</td>
<td>0.958</td>
<td>399.773E-12</td>
</tr>
<tr>
<td>6777N2</td>
<td>North/South</td>
<td>0.959</td>
<td>399.370E-12</td>
</tr>
<tr>
<td>6777E2</td>
<td>East/West</td>
<td>0.955</td>
<td>404.480E-12</td>
</tr>
</tbody>
</table>

### MASS POSITION CHANNELS

**Sample Rate:** 1 samples/sec

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>µV/Count</th>
<th>M/S²/Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>6777M8</td>
<td>Vertical</td>
<td>0.58</td>
<td>37.102E-9</td>
</tr>
<tr>
<td>6777M9</td>
<td>North/South</td>
<td>0.58</td>
<td>38.714E-9</td>
</tr>
<tr>
<td>6777MA</td>
<td>East/West</td>
<td>0.58</td>
<td>37.313E-9</td>
</tr>
</tbody>
</table>

### CAL SIGNAL MONITOR

<table>
<thead>
<tr>
<th>Channel</th>
<th>µV/Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>6777MB</td>
<td></td>
</tr>
</tbody>
</table>

### GPS RECEIVER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM</td>
<td>525000 Counts</td>
</tr>
<tr>
<td>At Temperature Reading</td>
<td>23°C</td>
</tr>
</tbody>
</table>

### POWER CONSUMPTION

**Digitiser Power Consumption:** 54mA @ 12v
### CMG-6T CALIBRATION SHEET T6B87

**WORKS ORDER:** 5683  
**DATE:** 24-May-2010  
**SERIAL NUMBER:** T6B87  
**TESTED BY:** S. Goddard

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Measurement</th>
<th>Acceleration</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>2 x 1186</td>
<td>16</td>
<td>0.00472</td>
</tr>
<tr>
<td>Mass Position</td>
<td>2 x 1196</td>
<td>15</td>
<td>0.00441</td>
</tr>
<tr>
<td>Feedback Coil</td>
<td>2 x 1192</td>
<td>15</td>
<td>0.00467</td>
</tr>
</tbody>
</table>

**Power Consumption:** 22mA @ +12V input  
**Calibration Resistor:** 51000

**NOTE:** A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.
POLES AND ZEROS TABLE

WORKS ORDER NUMBER: 5683

SENSOR SERIAL NO: T6B87

Velocity response output, Vertical Sensor:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^{-3} + j -23.56 x 10^{-3}</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 + j 135.392</td>
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<tr>
<td>-350</td>
<td>0</td>
</tr>
<tr>
<td>-75</td>
<td>0</td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: \( A = 585.8 \times 10^6 \)


Velocity response output, Horizontal Sensors:

<table>
<thead>
<tr>
<th>POLES (HZ)</th>
<th>ZEROS (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-23.56 x 10^{-3} + j -23.56 x 10^{-3}</td>
<td>0</td>
</tr>
<tr>
<td>-62.3816 + j 135.392</td>
<td>0</td>
</tr>
<tr>
<td>-350</td>
<td>0</td>
</tr>
<tr>
<td>-75</td>
<td>0</td>
</tr>
</tbody>
</table>

Normalizing factor at 1 Hz: \( A = 585.8 \times 10^6 \)


**NOTE:** The above poles and zeros apply to the vertical and the horizontal sensors and are given in units of Hz. To convert to Radian/sec multiply each pole or zero with \( 2\pi \) and the normalizing factor \( A \) should also be recalculated.
Earthquake spectral amplitude measurements (ESAM) (Moran et al., 2008) were made for individual events in the Antelope catalogue described in Chapter 3. Spectral amplitudes were calculated in 0.5 Hz bands from the FFT of a 12 second window around the largest peak in the waveform. The spectral amplitude measurements for each individual earthquake were plotted as a single vertical line with a colour scale representing the spectral amplitude of each band, and all earthquakes were plotted sequentially as individual vertical lines. While similar to a more traditional spectrogram representing continuous waveform data, the x-axis on the ESAM plot represents event number rather than time; however, we have converted these event numbers to their corresponding dates to allow the spectral content of each event to be observed over time.

ESAM at TBTN (Figure C1) and TBMR (Figure C2) shows that the spectral energy throughout the study period occurs predominantly below 6 Hz. Between April and September 2010, both TBTN and TBMR have events with energy between 1-6 Hz. In September 2010 frequencies below 3 Hz disappear at TBTN and high-frequency energy starts to appear, and at TBMR, frequencies below 208
2 Hz have disappeared by October 2010. These low frequencies do not re-appear until August 2011. Three swarms occur in September 2011, November 2011 and February 2012, and can be seen in the ESAM as periods with high spectral amplitudes in the 2-5 Hz range.

These plots allow for a more complete representation of the spectral content of each event than can be represented by plotting only the peak frequency of each event (Appendix A, Figure A4). However, despite the greater spectral information represented, we find that these plots are not an improvement over the peak frequency plots in terms of conveying the variations in spectral energy of events over time. A possible reason for this could be that there is too much information to be clearly displayed in a figure of this size, i.e. there are over 200,000 events and each event has 30 spectral amplitude measurements, giving over six million data points to be conveyed in this figure. This figure, when printed, is ~200mm wide, meaning each event is represented by a vertical strip of colour 0.001mm wide. Hence, bright areas that indicate dominant spectral energy will only show up if there are many consecutive events with the same spectral content. While this appears to be true for the lower frequencies (< 6 Hz), the high-frequency content is not as temporally consistent and therefore is not well displayed in these plots.
Figure C1. ESAM for all individual events at station TBTN from April 2010 until March 2013. Each event is drawn as a single vertical line with red (warmer) colours indicating higher spectral intensities and blue (cooler) colour indicating low spectral intensities over 0.5 Hz bands. Note that the x-axis is not a true time-axis, but represents individual events.
Figure C2. ESAM for all individual events at station TBMR from April 2010 until March 2013. Each event is drawn as a single vertical line with red (warmer) colours indicating higher spectral intensities and blue (cooler) colour indicating low spectral intensities over 0.5 Hz bands. Note that the x-axis is not a true time-axis, but represents individual events.
APPENDIX D:

EXAMPLE WAVEFORMS WITH BACKGROUND NOISE LEVELS

Example waveforms are plotted from six different periods throughout the study period to assess the noise conditions during the different periods. All events are plotted with two minutes of background data before and after the event. All events are filtered between 0.5 Hz and 20 Hz, which is the same filter as used during the single-station event detection method. From the six waveforms plotted the background noise level appears low enough not to interfere with the detection procedure. Some events have higher background noise than others; however, this is probably due to different wind/noise conditions during the selected days, rather than any systematic trend. The waveforms in May 2011, November 2011 and in March 2013 show small events either side of the main event, that were not detected by our single station event detection method.
Figure D1. Four-minute seismogram surrounding an event from the 2nd May 2010 at 01:20:50. Event is filtered between 0.5 and 20 Hz.
Figure D2. Four-minute seismogram surrounding an event from the 1st February 2011 at 00:03:50. Event is filtered between 0.5 and 20 Hz.
Figure D3. Four-minute seismogram surrounding an event from the 11th May 2011 at 07:27:10. Event is filtered between 0.5 and 20 Hz.
Figure D4. Four-minute seismogram surrounding an event from the 1st November 2011 at 00:05:50. Event is filtered between 0.5 and 20 Hz.
Figure D5. Four-minute seismogram surrounding an event from the 1st October 2012 at 02:18:00. Event is filtered between 0.5 and 20 Hz.
Figure D6. Four-minute seismogram surrounding an event from the 2\textsuperscript{nd} March 2013 at 01:05:00. Event is filtered between 0.5 and 20 Hz.
APPENDIX E:

CONTROL PARAMETER FILE (XCORR.CONF)

# mode - ANALYSE, PEAKMATCH, FFTPRECACHE, POSTPROCESS, BRUTEFORCE, FFTDOMINANTFREQ, PLOT2D, PLOT1D

mode = ANALYSE

# more logging
verbose = false

# data directories
dataset.full = /home/mrodgers/events/full
dataset.sample = /home/mrodgers/events/sample

# expected length of files - if any files are not this length, will be zero padded or truncated
expected-file-line-count = 4000

# locate peak within peak-range readings, then return a window around it
# Antelope detected data @50Hz check for peaks between 5-40seconds, calculate 4second
# window before & 8 second after
crop = true

crop.min-peak-range = 250

crop.max-peak-range = 2000

crop.window-before-peak = 200

crop.window-after-peak = 400

# top K peaks (min and max), ordered by amplitude, which will be aligned together
# run-time varies as O(top-k-peaks ^ 2) - every event's top K peaks are aligned against every
# other event's top K peaks
top-k-peaks = 3
# sample events every sampling-stride entries
# run-time varies as O(1/sampling-stride)
sampling-stride = 3

# only calculate xcorr values for values where the amplitude is higher than this fraction of the peak amplitude
# the final xcorr value for a well-matching pair is dominated by the multiplication of two peaks together (1000 * 1000 >> 50 * 50)
# setting this to a non-zero value means eliminating a large amount of noise from the calculations, and drastically speeding up the calculation
# tweak this value in ANALYSE phase: too high -> false negatives. too low -> performance degradation
top-amplitude-threshold = 0.3

# threshold for candidates to be included
# this will be lower than the final xcorr calculated value
# tweak this value in ANALYSE phase: too high -> false negatives. too low -> too many false positives for post-processing
candidate-threshold = 0.55

# threshold for the final FFT xcorr post-process step
final-threshold = 0.8

# number of threads to use in the PEAKMATCH and POSTPROCESS steps. set this equal to the number of processor cores for optimal performance.
# (performance calculations in the ANALYSE phase don’t use multi-threading, so extrapolations may be inaccurate by this factor)
threads = 2

# in-memory LRU FFT cache for FFT xcorr calculations.
# set to zero to disable this cache
fft-memory-cache-size = 1000

# move the origin to zero before performing any calculations (subtract mean amplitude from all readings)
normalise-events = true

dominantfreq.band-width = 0.5
dominantfreq.filter-below-hz = 1
dominantfreq.filter-above-hz = 15
# Other stations
dominantfreq.sample-rate = 50
dominantfreq.top-freq-count = 5

# space-separated frequency (hz) bands (eg [1.3-4.5]) to calculate mean spectral amplitudes across
dominantfreq.mean-frequency-amplitude-bands = [1-2] [2-3] [3-4] [4-5] [5-6] [6-7] [7-8] [8-9] [9-10] [10-11] [11-12] [12-13]

# plot a single-band frequency spectrum on one line
plot.1d.tiny = true

# duration of bands to slice event into for 2d plot
plot.2d.bucket-duration-sec = 1

# VERTICAL, HORIZONTAL or SHADED
plot.2d.gradient = SHADED

# size of frequency bands to divide sample into for plot
frequency.band-hz = 1