To Erupt or Not to Erupt? That is the Question: Extremely High Levels of Background Seismicity and Lack of Eruptivity from 2003-2019 at Gareloi Volcano, Aleutian Islands, Alaska

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To Erupt or Not to Erupt? That is the Question: Extremely High Levels of Background Seismicity and Lack of Eruptivity from 2003-2019 at Gareloi Volcano, Aleutian Islands, Alaska

By

Kiana Tamarie Harris

Accepted in Partial Completion of the Requirements for the Degree Master of Science

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Master’s Thesis

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Kiana Tamarie Harris

May 3, 2022
To Erupt or Not to Erupt? That is the Question: Extremely High Levels of Background Seismicity and Lack of Eruptivity from 2003-2019 at Gareloi Volcano, Aleutian Islands, Alaska

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Kiana Tamarie Harris
May 3, 2022
Abstract

Mount Gareloi, one of the westernmost volcanoes in the Aleutian arc, has not erupted since 1989, yet it continuously exhibits extremely high levels of background seismicity. Hundreds of volcanic earthquakes are recorded per day on the island since seismometer installation in 2003. I analyzed and classified seismic data collected from 2003-2019 to explore the geophysical processes causing this consistent seismicity with no subsequent eruptive activity. Analysis of waveform and corresponding spectra indicate the vast majority of Gareloi earthquakes are characterized by frequencies between 1 and 5 Hz, which are typical of long-period (LP) events, and these events are particularly dominant from 2003-2007.

I relocated 5,884 earthquake hypocenters calculated by the Alaska Volcano Observatory (AVO) using the algorithm hypoDD. From 2003-2007, hypocenters locate shallowly between 2 and 10 kilometers depth and are primarily beneath the north half of the island. Meanwhile, seismicity from 2016-2019 was typically deeper, between 6 and 16 kilometers depth and included more high-frequency (HF) events, characterized by frequencies above >5 Hz. Although relocated hypocenters have similar spatial distribution to the initial locations, seismicity from 2003-2007 clusters more tightly and vertically beneath the island, whereas earthquakes from 2016-2019 are scattered throughout the region with no obvious clustering. Cross correlation of the data reveals multiplet activity occurred from April to July 2007 with minimum correlation coefficients of 0.7, tightly clustered at the northern end of the island and may be the result of heated fluids repeatedly moving through a single fracture within the edifice. This multiplet activity may have been a failed eruptive event.

Overall, Gareloi seismicity is broadly distributed and dissimilar, indicating a plethora of seismic sources within the volcanic edifice. I attribute Gareloi’s constant LP seismicity to the movement and exsolution of volcanic fluids and gases within a highly fractured, heterogeneous volcanic edifice and magmatic system. I ascribe the sporadic HF activity to brittle failures that result from an accommodation of magmatic stresses on surrounding rock and regional tectonics. Further studies and imaging of Gareloi are necessary to fully understand the magmatic system.
and geophysical processes producing these high levels of background seismicity and lack of eruptivity in order to better predict signs of volcanic unrest.
I would like to acknowledge that Mount Gareloi resides within the traditional lands of the Unangam Tanangin people. They continue to enrich the communities of the Aleutians with their heritage and culture. Thank you for your stewardship in taking care of and preserving these incredible lands and volcanoes.
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Introduction

A primary objective in volcano monitoring is to use the seismicity to make inferences about a volcano’s expected behavior and monitor for drastic changes within the system that occur in advance of eruptions. In many cases, real-time seismological data is consistently recorded at volcanoes, making seismology the most reliable physical characteristic that scientists can use to infer changes in a volcanic system (White & McCausland, 2019). This forecasting method is deployed at a variety of volcano types, especially at stratovolcanoes that have been dormant for multiple decades (White & McCausland, 2019).

Rapid changes in earthquake locations, signal type, depth, magnitude, and frequency are several factors seismologists observe for shifts in volcanic activity and potential eruptive activity. Hypocenter locations in volcanic environments and changes in type of seismicity are of particular interest (Chouet, 1996; White & McCausland, 2019), as changes in the location, quantity, and magnitude of earthquakes have been directly linked to impending volcanic eruptions (McNutt, 2002). Through analyzing these patterns and changes in seismicity, preemptive action and evacuations can be instituted and the impacts can be drastically reduced, such as with the 1991 eruption of Mount Pinatubo in the Philippines (White & McCausland, 2019). Other examples of increased seismicity to forecast imminent eruptions include Mount St. Helens in 1980, Usu, Japan in 1910, 1944, and 1978, and Arenal Volcano, Costa Rica in 1968, among others (McNutt, 2002; White & McCausland, 2019).

In this study, I analyzed 5,884 earthquakes for signal and frequency type, and hypocenter relocations, at Mount Gareloi to constrain the source area(s) of seismic activity and to determine if these sources were the result(s) of changes in the volcanic system between 2003-2019.

Although the Aleutian Islands are among the best-monitored volcanic chains in the world, there have been few extensive studies performed on the westernmost end of the chain due to their remote locations and difficult accessibility. Seismicity originating around stratovolcanoes, such as those in the Aleutian Islands (Figure 1), is of concern, as this can
indicate unrest and be a potential precursor for imminent eruptions and associated hazards. In particular, the volume of ash stratovolcanoes can produce is hazardous for human health and air travel. This includes Mount Gareloi, a small ~1,600 meter high, double-coned stratovolcano that is not visible from any population center (Miller et al., 1998; Coombs et al., 2008; Figure 1).

Gareloi is historically one of the most active volcanoes in the Aleutian arc, with at least 16 known eruptions since its discovery in 1760 (Coombs et al., 2008; Table 1). Many eruption reports are vague (Coombs et al., 2008), with the best-documented eruptions occurring within the last century, including its last confirmed eruption in 1989 and an unconfirmed but possible eruption in 1996. However, Gareloi displays extremely high levels of background seismicity throughout the island and its surrounding region (Coombs et al., 2008; Figures 2 & 3).

Mount Gareloi is located directly beneath a heavily traveled aviation route between North America and Asia, making it important to provide warning for eruptions that could impact air travel. The greatest hazard Gareloi poses is ash plumes, which can rise thousands of meters in the air (Coombs et al., 2008), and have the potential to travel hundreds of kilometers away. This poses a substantial hazard to passing aircrafts, as small particle size and glassy composition of ash from volcanic eruptions can easily enter aircrafts and wreak havoc on critical systems, such as the engines, navigation, and windshield (Guffanti et al., 2010). Therefore, it is necessary to understand the seismicity and be able to use it to predict an eruption at Gareloi to help the Federal Aviation Administration (FAA) prepare alternative consumer and commercial flight paths and thus avoid tragedy. In this study, I take an in-depth look at Gareloi seismicity to infer what geophysical process are instigating these numerous earthquakes and interpret if any of these process or changes in these processes are potential indicators for future eruptions.

Since the installation of seismometers in 2003, Gareloi has exhibited continual seismicity, with dozens and up to hundreds of small earthquakes per day (Caplan-Auerbach & Prejean, 2005; Figure 3). These earthquakes are difficult to locate, as only a fraction of the events are large enough to be recorded well by an adequate amount of stations in the seismic network. The majority of the earthquakes at Gareloi are long-period (LP) events, which typically have emergent onsets and lack clear S-waves to aid in event location; as a result of these waveform characteristics, dozens, and potentially hundreds, of additional events to go “unseen” within the AVO earthquake catalog (Dixon et al., 2019). Furthermore, source mechanisms for
these earthquakes are challenging to determine, in part due to the difficulty in accurately locating them.

At other volcanic settings around the world, including other volcanoes in the Aleutians, the levels and types of seismicity found at Gareloi would likely accompany volcanic unrest and foreshadow eruptions (Chouet, 1996). At Gareloi, however, these high rates of seismicity are normal background seismicity and do not appear to correlate with impending eruptions (Caplan-Auerbach & Prejean, 2005; Coombs et al., 2008; Coombs et al., 2012; Dixon et al., 2020). Based on historic observations, scientists have postulated that Mount Gareloi experiences a volcanic eruption every few decades after a period of dormancy (Coats, 1959; Coombs et al., 2008; Table 1), but as no eruptions have occurred since seismometers were deployed, the character of its eruptive seismicity is unknown.

The only other volcano in the Aleutian Islands that has demonstrated similar levels of seismicity to Gareloi is Shishaldin Volcano (Petersen, 2007), but, unlike Gareloi, that volcano has erupted in recent years and has been extensively studied. Additionally, while Shishaldin exhibits extremely elevated levels of LP seismicity, the earthquakes comprise several families with highly similar waveforms, indicating the presence of non-destructive repetitive source mechanism(s) (Petersen et al., 2005; Petersen, 2007).

The vast majority of Gareloi earthquakes are classified as long-period (LP) with shallow hypocentral depths of 2-10 km and peak frequencies between 1-5 Hz (Figure 4A). LP events such as these are often observed in thermal systems and are thought to be caused by the movement of fluids such as water or magma (Chouet, 1996). However, Gareloi also experiences higher frequency (HF) seismicity above 5 Hz that occurs at deeper hypocentral depths of 6-16 km (Figure 4B). These HF events are the result of shear failure, which may stem from either regional or volcanic stresses (McNutt, 2002). Gareloi has also exhibited instances of volcanic tremor, which has the spectral character of long-period events, but maintains a longer, continuous signal (White & McCausland, 2019).

No in-depth studies have been conducted on Gareloi’s unusual seismicity. Although Caplan-Auerbach and Prejean (2005) reported on the high levels of seismic activity and lack of volcanic eruptions, the study was preliminary and only an abstract was published. Here, I
relocate and classify, based on the frequency content, all earthquake hypocenters determined by the Alaska Volcano Observatory (AVO) at Gareloi from 2003-2019. I then use the new hypocenters and associated classification to infer the geophysical processes and source mechanism(s) instigating Gareloi’s abundant seismicity. This analysis provides a basis for understanding ongoing volcanic seismicity at Gareloi and can be used diagnostically in evaluating future volcanic unrest.
Background

Volcano Seismology

Typical signals found at volcanic settings are high-frequency events (HF), long-period (LP) or low-frequency (LF) events, explosion earthquakes, associated with ground coupling of air-waves from explosive eruptions, tremor which consists of continuous signals that typically resemble LP events, hybrid events which contain seismic signals of multiple frequencies in a single waveform, very long-period events (VLP), and deep long-period events (DLP) (McNutt, 2002). Surficial non-volcanic events, such as glacial slip, calving, or landslides, and volcanic events, such as pyroclastic flows and lahars, can also produce ground shaking that is recorded by local seismometers (McNutt, 2002). For this study, I primarily focus on the occurrence of LP and HF activity at Mount Gareloi, as these are the most prominent signals on the island, in order to interpret the seismic source mechanisms.

Long-period events are typically characterized by frequencies of 1-5 Hz and are thought to result from the movement of fluids such as magma, water, or gas in a volcanic edifice (Chouet, 1996). One significant characteristic of LP seismic signals is the lack of a clear S-phase arrival and an emergent P-phase (McNutt, 2002; Figure 4A). LP seismic activity is particularly useful in understanding volcanic processes, as it provides insight toward a system’s fluid dynamics. Increases in LP activity have been linked to depressurization in a magma reservoir and act as early warning signs for imminent eruptions (White & McCausland, 2016; White & McCausland, 2019), one such case being the 1991 Mount Pinatubo eruption (Harlow et al., 1996).

High-frequency events are characterized by frequencies >5 Hz (Figure 4B) and are most often associated with shear slip on faults within a volcanic area; HF events display clear P- and S-wave arrivals and often occur in swarms (McNutt, 2002). HF activity in volcanic settings is not limited to tectonic stresses alone and may be induced by cracks and fracturing within the volcanic edifice that may result from magmatic activity. It has been noted that increases in
volcanic-tectonic (VT) events, one form of HF seismicity, may act as the first precursor to renewed volcanic activity (Roman & Cashman, 2006; White & McCausland, 2016).

**Gareloi Geology and Regional Tectonics**

Spanning 3,800 km from Russia to Central Alaska, the Aleutian and Alaskan subduction zones form a series of volcanic islands and a zone of intense seismicity (Ruppert et al., 2007). Approximately 40 active volcanoes in the arc have erupted in historic times and over 80 have erupted in the last 10,000 years, including Mount Gareloi (Miller et al., 1998).

As the Pacific Plate subducts beneath the North American Plate, the angle of convergence becomes more and more oblique toward the west until it transitions into strike-slip motion at Attu Island (Geist et al., 1988; Ruppert et al., 2012). To compensate for this oblique subduction, portions of the overriding North American Plate are thought to undergo clockwise rotation in a series of five forearc blocks (Geist et al., 1988; Ruppert et al., 2012; Figure 5). In addition to the changing subduction angles, the rate of convergence also varies across the arc (DeMets et al., 1990; DeMets et al., 1994; Buurman et al., 2014). Furthermore, this convergent boundary has seen approximately two-dozen earthquakes over magnitude 7.5 in the past century (Ruppert et al., 2007; Tibaldi & Bonali, 2017; [https://earthquake.usgs.gov/earthquakes/search/](https://earthquake.usgs.gov/earthquakes/search/)).

Gareloi is one of the westernmost Aleutian volcanoes, ~2000 km from Anchorage and ~150 km from the nearest population center of Adak, Alaska. Gareloi Island is a small, 8x10 km island composed almost entirely of a ~1,600 m high double-cone stratovolcano, Mount Gareloi, and its eruptive products (Coombs et al., 2008; Figure 6). The island resides within the Delarof forearc block (Geist et al., 1988; Coombs et al., 2008; Ruppert et al., 2012; Figure 5).

During Coats’s (1959) original study, he noted the island consisted of layers of scoria and basalt of varying compositions and thickness at different sections of the volcano. Additionally, after his mid-1940’s reconnaissance to Gareloi (Coats, 1959; Coombs et al., 2008), Coats suggested that Gareloi eruptive products ranged from basaltic to andesitic composition. Recent eruptions have drastically altered the island; the 1929 eruption resulted in at least 16 craters
leading up the southeastern flank (Coats, 1959; Coombs et al., 2012). According to Miller et al. (1998) and Coombs et al. (2012), these craters range in diameter from 80m up to 1600m.

While Gareloi’s North Peak has been considered to be the primary volcanic vent, active fumaroles reside within the South Peak, and both summits have produced effusive and explosive eruptions in the past (Coombs et al., 2008; Figure 6). Furthermore, there is a known eruptive fissure on the south-southeastern flank that formed during the 1929 eruption (Nakamura, 1977; Coombs et al., 2012; Figure 7). A significant volume of landslide debris has been mapped to the north, northwest, and east, encompassing the majority of the volcano’s submarine flanks (Coombs et al., 2007; Coombs et al., 2008; Figure 8). Landslide slip zones can be potential sources of seismicity at volcanoes (McNutt, 2002), so here I note these prior debris flows to investigate these areas as a possible source for non-LP seismicity.

Though samples have not been radiometrically dated, based on the ages of samples from neighboring stratocones, Gareloi’s oldest products are assumed to be Pleistocene (Coombs et al., 2012). Petrologic analysis reveals Gareloi lavas and pyroclastic products range from latite to trachyte in composition, and the two distinct lava compositions are neither separated by time nor location (Coombs et al., 2012; Figure 7). This study suggests there may be multiple sources feeding into Gareloi’s magma reservoir, but this has not been confirmed (Coombs et al, 2012).

**Eruptive History**

From its initial discovery in 1760 by the Bering Expedition, Mount Gareloi has been known to be volcanically active (Miller et al., 1998). The 18<sup>th</sup> through 20<sup>th</sup> centuries saw at least 16 instances of reported eruptive activity (Coombs et al., 2008; Table 1). However, Gareloi is remote and not visible from any population center, so the majority of the accounts of Gareloi eruptions are vague at best, with descriptors such as “smoking” or “fire-belching” in Table 1 (Coombs et al., 2008), as witnessed by crewmembers on passing ship or aircrafts. Coats (1959) and Frasier and Barnett (1959) provided the most detailed understanding of the island’s geology during the twentieth century, including the aftermath of its largest eruption in 1929, until the reconnaissance performed in the early 2000s by AVO scientists.
Of the 16 known historic eruptions, the best studied is the explosive 1929 eruption, that includes several eyewitness accounts by Adak residents (Coats, 1959; Miller et al., 1998; Coombs et al., 2008; Table 1). The 1929 eruption is also classified as the largest of Gareloi’s historical eruptions, though the exact volume of material ejected is unclear (Coombs et al., 2008) and was the primary focus of Coats’ expedition seventeen years later (Coats, 1959; Coombs et al., 2008). This eruption is speculated to have continued into 1930 and resulted in the explosion craters on the volcano’s southeast flank (Coats, 1959; Coombs et al., 2012).

Following the 1929 eruption, Gareloi’s South Peak erupted effusively, but as with the majority of Gareloi eruptions, the dates, progression, and extent of these effusive eruptions is unclear (Coombs et al., 2008). Regardless, this effusive eruption produced overlapping ‘a’a lava flows extending 800 meters from the South Peak crater and down the southeast flank of the island (Coombs et al., 2008; Figures 6 & 7). Between 1980 and 1996, at least five eruptions were observed by either aircraft pilots and crew or via satellite imagery (Miller et al., 1998; Coombs et al., 2008). Four of these five eruptions were explosive in nature with ash plumes ranging from 1,500 to 40,000 feet above sea level. Of these eruptions, the 1996 activity is the least well-documented and remains a questionable event (Coombs et al., 2008; Table 1).

The 1989 event is the most recent confirmed eruption for Mount Gareloi where a 2,300 foot ash plume was observed above North Peak from a commercial jet (Reeder, 1992; Coombs et al., 2008; Coombs et al., 2012), and the volcano has remained volcanically quiescent since. Aside from this, North and South Peaks have displayed hydrothermal activity in the form of high-temperature, active fumaroles (Coombs et al., 2012). The South Peak fumaroles are more active than those residing on the North Peak and are considered the primary areas of degassing for the volcano (Coombs et al., 2012; Fischer et al., 2021).

Previous Work

Due to Gareloi’s location, accessible only by helicopter or ship, formal studies of the geology of the volcano have been limited. The majority of these investigations incorporated Gareloi as a small component in larger, regional-scale projects, ranging from studies on regional tectonics (Nakamura et al., 1980; Montanaro & Beget, 2011; Ruppert et al., 2012; Brown et al.,
to submarine landslide and edifice failure at volcanoes (Coombs et al., 2007) and gas emissions of western Aleutian volcanoes (Fischer et al., 2021). None of these studies, however, focuses solely on Gareloi.

In 2003, Gareloi was brought under closer observation by AVO as part of their initiative to monitor every historically active volcano in the Aleutian arc (Coombs et al., 2012). As part of this effort, AVO scientists led a field campaign on Gareloi, which included geologic mapping and the deployment of the Gareloi six-station seismic network (Caplan-Auerbach & Prejean, 2005; Coombs et al., 2008, Coombs et al., 2012; Figures 7 & 9). A preliminary assessment of Gareloi’s volcanic hazards was published in 2008 (Coombs et al., 2008).
Data

Three types of data for this project were provided by AVO: 1) digital waveforms, 2) P- and S-wave phase arrivals, and 3) a catalog of earthquake hypocenters, magnitudes, and origin times. The data analyzed in this project were collected between October 2003 and July 2019 when the Gareloi seismic network was upgraded to broadband instruments. Due to frequent station outages from 2008 to 2015 where no more than three seismometers in the Gareloi seismic network functioned, the seismic catalog is considered incomplete during this period.

Of the six instruments comprising the Gareloi seismic network five were installed on Gareloi island (GAEA, GALA, GANE, GANO, GASW) itself and one on Kavalga Island (GAKI) ~20 km to the south (Figure 9). Until the network upgrade in 2019, GASW was the only 3-component station (a 2-Hz, L22); the remaining five are solely vertical-component seismometers (1-Hz, L4s). I focused primarily on data from seismic stations on Gareloi and Kavalga islands, and for larger earthquakes, I supplemented with data from nearby networks on Tanaga, Kanaga, and Great Sitkin volcanoes.

Waveform data, as the name suggests, are the time series data for discrete earthquakes on Gareloi from all stations. Phase data includes manually determined P- and S-wave arrival times on all stations that registered Gareloi seismicity. Phase data were used for hypocentral relocation using hypoDD (Waldhauser & Ellsworth, 2000), and cross correlation codes to be used on waveforms were provided by Dr. Zhigang Peng (http://geophysics.eas.gatech.edu/people/cwu/teaching/hypoDD/hypoDD.html). After performing hypoDD trials and cross correlation, relocated hypocenters were plotted with Wessel et al.’s (2013) Generic Mapping Tool (GMT).

Catalog data were separated into three subsets based on the overall health of the Gareloi seismic network between 2003 and 2019. The first subset consisted of hypocenters from October 2003 to December 2007, when the network was in excellent health, and comprises over half the catalog with a total of 3,594 events. The second subset covers 2008 through 2015, when the
network experienced frequent outages. Because of this, the catalog only includes 413 events, and represents a substantial data gap for the study. The third and final subset of catalog data is from 2016 to 2019, when the network was restored back to working condition. There are 1,877 events during this time period. Catalog data were used both for hypocentral relocation through hypoDD (Waldhauser & Ellsworth, 2000) and to compare variables, such as the month earthquakes occurred, depths, magnitude, and signal type.

To identify earthquakes, AVO utilizes a short-term average/long-term average (STA/LTA) at all volcanoes from the incoming signal from each station within the Earthworm system (Johnson et al., 1995). If that STA/LTA surpasses a particular value on three stations, an earthquake is declared and manually reviewed. After events are detected by the STA/LTA algorithm, waveforms are extracted from the continuous record of seismicity. It must be noted the Earthworm STA/LTA algorithm configured at AVO has a long-term preference for detecting high frequency events due to their clear and easily identifiable phases, where the STA is 1s and the LTA is 8s (Dixon et al., 2005; Power, personal communication, 2022).

Following the extraction of the waveform data, seismic analysts at AVO manually review and identify P- and S-wave phase arrivals and measure the maximum amplitude of the seismic waves (Dixon et al., 2019). Finally, AVO calculates earthquake hypocenters and magnitudes to create the catalog data. From 1989-2012, AVO used the program Hypoellipse (Lahr, 1999) to locate earthquakes, and in 2012, they switched to Hypoinverse (Klein, 2002). After a comparison of the two algorithms yielded similar hypocenter locations, Power et al., (2019) created a consistent catalog for the entire time-period using Hypoinverse. The locations, origin times, and magnitudes comprise a catalog of 5,884 earthquakes located at Mount Gareloi between 2003 and 2019. As not all detected earthquakes are locatable, and not all seismic events trigger a response at the seismic stations, the catalog only contains a subset of Gareloi events.
Methodology

Waveform & Spectral Analysis

Data processing for this project began with analysis of the frequency of waveform data to determine the types of earthquakes occurring on Gareloi. To do this, I plotted waveforms and associated spectrograms for all Gareloi earthquakes for the six stations (see Figure 4 for a partial example). Spectrograms use a color palette to depict a visual representation of an earthquake’s frequency and strength; the frequency it displays helps corroborate the waveform’s signal type. Events were categorized as LP, HF, or Unclassified. Waveform and spectrograms with emergent P-wave arrivals, poor S-wave arrivals, and peak frequencies <5 Hz were classified as LP earthquakes (Figure 4A). Meanwhile events with clear P- and S-waves and peak spectral frequencies >5 Hz were labeled as HF (Figure 4B). In cases where, waveforms and spectral content were difficult to discern due to noise burial, or could not be corroborated by more than one other station; the events were labeled as Unclassified.

There were also cases were a single waveform file contained multiple events which contained combinations of LP and HF signals. Typically, when double events occur, AVO processing generates a second waveform file for the second event (Power, personal communication, 2021; Caplan-Auerbach, personal communication, 2021). In order to investigate if a second waveform files for the second events in double-waveform files occurred, I reviewed all double events by checking the earthquake timestamps. If the timestamps did not match up within a few seconds, these double-events were counted as a single event by the station, and thus the second signal in the waveform did not receive its own file; this was the case for most instances of double events. Therefore, when I encountered these multiple signal events, I considered them as a separate classification, but these events will not be further elaborated upon.

In addition to waveform and spectral analysis, I performed cross correlation of the waveforms using the GISMO suite of MATLAB scripts (Thompson & Reyes, 2018; see Appendix A). This took all waveforms and cross-correlated them against all other waveforms
within the full dataset, evaluating the similarity between events, called multiplets. These multiplets imply the repetition of the same location and source mechanism for these earthquakes.

For the cross correlations, I focused data from stations GAEA, GALA, and GANE, as these three seismometers exhibited the best health throughout the study. Of these three, I primarily utilized station GAEA, as this seismometer functioned well with little to no technical issues or data interruptions during the entirety of the study. After cross-correlating all earthquakes recorded at GAEA, I then calculated subsets of detected multiplets with a minimum of a 0.7 correlation coefficient for further examination.

The waveform data provided by AVO begin around the first minute before the P-wave of the earthquake, and contain clear enough P- and S-wave arrivals, allowing them to be locatable. Most LP events have emergent P-waves and poorly-defined S-waves; HF waves show more reliable arrivals for both P- and S-waves, allowing them to be better and more easily located. However, use of continuous data allows for closer examination of signal patterns and provides additional insight into such things as potential seasonal effects. These data consists of all seismic activity recorded by the seismometer including events that are not included in the AVO catalog. The Incorporated Research Institutions for Seismology (IRIS) began archiving continuous data for Gareloi stations from 2008 onward. As such, continuous data from station GAEA and one additional Gareloi Island station were accessed from the IRIS data center for days during summer and winter, typically in June and November, plotted in both the time and frequency domains (Figures 10 & 11).

_Hypocentral Relocation_

To precisely locate Gareloi earthquakes, I applied the relative relocation algorithm HypoDD developed by Waldhauser and Ellsworth (2000) to the 5,884 earthquakes located by AVO. HypoDD uses a combination of catalog and cross-correlated arrival times to perform relative relocations on pairs of earthquakes at multiple stations (Waldhauser & Ellsworth, 2000). HypoDD compares the difference in the theoretical and observed travel times, or differential travel times, between two individual earthquakes at the same station to infer how close their focuses are spatially (Waldhauser & Ellsworth, 2000). If the travel times are similar, hypoDD
declares the two earthquakes a pair, then compares the observed and theoretical travel times. When the distance between two separate hypocenters is small compared to their distances to the same station, hypoDD considers the distance and ray paths to be similar and deems the events neighbors (Waldhauser & Ellsworth, 2000). Comparing relative rather than absolute locations reduces overall error as hypoDD is less reliant on the velocity model, which is poorly constrained at Gareloi (Dixon et al., 2019). It must be noted that hypoDD discards any hypocenters that occur above sea level.

If events are tightly clustered, the overall area of hypocenter locations can then collapse into more constrained area (Waldhauser & Ellsworth, 2000), particularly if both catalog and cross correlated data are used. If events are not clustered tightly, hypoDD may still move hypocenters, but the cluster may not shrink in size.

When two earthquakes contain similar waveforms at a shared seismic station, the origin of each can be assumed to be highly similar (Geller & Mueller, 1980; Waldhauser & Ellsworth, 2000). Because cross-correlation selects phase arrivals based on this waveform similarity, it is less significantly impacted by background noise, and decreases the location uncertainty (Geller & Mueller, 1980; Waldhauser & Ellsworth, 2000). Error from manual selecting P- and S-waves is also reduced with use of cross-correlated arrivals.

Prior to relocation with hypoDD, data are preprocessed via a program called ph2dt, which uses observed travel times to find neighboring events (see Appendix B). Initial processing via ph2dt results in an output file of differential travel times, used for subsequent hypoDD trials. Particularly restrictive parameter settings identified few neighbors for the earthquakes, thus decreasing the number of events hypoDD relocated. Due to the size of the dataset, I wanted to relocate as many events as possible, I chose less restrictive parameters for ph2dt and more restrictive for hypoDD (see Appendix B). For example, one of the less restrictive parameters chosen for ph2dt was a maximum separation in kilometers between hypocenters (MAXSEP), where I used primarily 5 km; for hypoDD, the parameters WDCT and WDCC, which weight catalog and correlated arrivals as a function of distance, are similar to MAXSEP. I typically used distances of 2, 3, or 4 km for iterations (see Appendix B).
Many trials produced near identical results regardless of input parameter adjustments. Trials where nearly all of events were relocated (i.e. not disregarded by ph2dt before hypoDD), place hypocenters in a relatively tight, vertical area beneath the island. Relocations occur in a broadly similar spatial pattern as initial locations, so the trials whose parameter combinations resulted in the clearest tightening least scatter; I considered these the “best” parameter sets. Many of Gareloi’s earthquakes occur in similar locations to other events with similar frequency content. I considered plots that mostly clearly illustrated location trends to be the best representation of the island’s seismicity.

Hypocentral relocations performed with the hypoDD “best” parameter sets contain an unknown degree of uncertainty, however. The downside of hypoDD is that the program’s ability to quantify error locations is less than ideal, so although relative locations appear to tighten up on the map, this may not necessarily be reflective of the actual hypocentral relocations. As such, hypoDD relocations are considered relative rather than absolute, and tightened locations may not necessarily be better, as the earthquakes may not actually be as closely located as the program generates or closely related at all.

HypoDD trials were initially run with catalog data only. Although many Gareloi earthquakes lack a clear S-phase, I performed trials using both P- and S-phases to maximize the number of phases seen by stations. All trials used data from any station within 225 km of the event pair and used any event with a minimum pick weight of 0, which considers all events in the catalog. This minimum weight is a measure of the reliability of the earthquake’s pick times for P- and S-arrivals, between 0 and 1, where 0 indicates a less reliable pick and 1 is considered the best (Waldhauser, 2001), as determined by AVO analysts. The minimum weight was increased to 1 in later trials, to constrain results using only the most reliable picks. Note that the use of a 0-1 scale in hypoDD differs from the 0-4 scale used by programs such as Hypoellipse and Hypoinverse in which 0 is considered most reliable.

Tests were run with maximum hypocentral separation between event pairs of 8, 5, or 3 km. Each subset underwent multiple trials with different combinations of the maximum number of neighbors per event, minimum number of links required to define a neighbor, minimum number of links per pair, and maximum number of links per pair (MAXOBS) (Waldhauser,
2001). In most trials, MAXOBS was set to no more than 50; for the 2003-2007 trials, I used MAXOBS of 100 in earlier trials and later decreased this to 50.

Due to the large number of events at Gareloi, I generally required phase arrivals from a minimum of 5 or 6 stations (a parameter defined as OBSCT for catalog data in the hypoDD input file) to locate event pairs. As the 2008-2015 period had poor network health, it was rare to have more than four functioning stations, so the threshold was set at 3-4 stations. Because there are only five stations on Gareloi Island, setting a minimum of six stations required the use of at least one off-island station, and thus only the largest and least-noisy events could be located. As such, earthquakes relocated with a minimum of 6 stations are the best recorded and most reliable events in the catalog. For this study, however, all my results will focus on the changes I see when I require a minimum of 5 stations, as it gives the broader view of Gareloi’s seismicity.

HypoDD trials were run with an 8-layer velocity model (NLAY) with a P-wave velocity/S-wave velocity ratio (RATIO) of 1.73. The velocity model chosen is a standard model developed for Alaska by Fogleman et al., (1993) and used by AVO for volcanic earthquakes in areas where a volcano specific model has not been developed (Dixon et al., 2019).

After initial tests using only catalog arrival times, I then performed several hypoDD tests using cross-correlated arrival times, which were obtained through the cross correlations of waveform data. This waveform cross correlation was performed using Dr. Zhigang Peng’s Waveform Cross Correlation Package (http://geophysics.eas.gatech.edu/people/cwu/teaching/hypoDD/hypoDD.html) to generate travel times based on cross-correlated arrivals rather than catalog arrivals to better constrain travel times and hypocenter locations (see Appendix B). This method was used on the 2003-2007 data subset, 2016-2019 subset, and the full 2003-2019 data set. The cross-correlated times were then combined with catalog arrivals to better constrain hypocentral localities. With the addition of cross-correlated data, I generally only required a minimum of 3 or 4 stations (a parameter called OBSCC in the hypoDD input file), as there was less cross-correlated data available for relocating hypocenters.
Station Health Observation Tests

To observe how different stations affected the overall data and hypoDD parameters, I ran catalog trials based on station health. To do this, I tested the effect each station had by locating events with a single station removed from my stations list; for example, one trial ran with station GAEA absent, another with GAKI absent, etc (Figure 12). I ran these missing station trials with catalog data and a minimum of 5 stations, as this provided a broader view of the region and did not need to reach out to another network’s stations to run hypoDD.

Overall, missing stations altered the overall shape of relocations slightly (Figure 12), but most events still locate in a relatively similar area and shape relative to relocations that incorporate all six stations (Figure 12A).

These tests show that station GAEA (Figure 12B) is critical for locations during the 2016-2019 time frame, as many events are not relocated when it is absent. This is because station GAEA experienced the best overall health in the entire network, working almost constantly throughout the study period, making it my most reliable station for identifying and relocating events. When station GAEA was removed from the list, there were often fewer than 5 reliable signals, and thus events could not be relocated well. When GAKI (Figure 12C) was excluded, relocations were not significantly impacted. GAKI is the station that is located on Kavalga island, 20 km to the south of Gareloi, so it is only useful for the largest Gareloi events.

Relocations without GALA or GANE (Figures 12D & 12E) have a minor effect on the relocations, particularly for later years. If either of these stations are removed, there are slightly fewer events which are slightly less constrained, but overall hypocenters are largely unaffected.

As with station GAKI, when GANO (Figure 12F) is absent, relocations do not display much, if any, difference from when all six stations are present. Throughout the entirety of the 16-year study, GANO experienced frequent outages, even when the network was in overall good health. GASW (Figure 12G) is also necessary for hypoDD to relocate hypocenters for the entire timeframe of the study, likely because this is our only three-component instrument and is used the most for S-waves.
Results

Because not every earthquake on the island triggers the STA/LTA algorithm, the results discussed below only represent the located events during the study’s time frames. Gareloi’s total earthquake rate is likely to be a significantly larger total when the smaller, non-detected earthquakes are accounted for. I looked at the relative number of events recorded in continuous data acquired using the IRIS database (Figures 10 & 11) and compared it to the total number of events listed in the catalog on randomly selected days in the 2008-2019 subset and confirmed on these days, there are substantially more earthquakes in the continuous data than are in the catalog for both 2008-2015 (Figure 10) and 2016-2019 (Figure 11).

In Figures 10 and 11, fewer than 10 events are listed in the catalog for the entire days, but the continuous data shows at least two-dozen within the two-hour windows shown. I performed several STA/LTA tests of continuous data from the more recent years (2016-2019) to gain a sense of the number of events that did not meet the triggering threshold of AVO’s STA/LTA. These tests were performed on two-hour time frames from (a) a clear summer day with low wind with fewer than 10 events in the catalog, (b) a clear winter day with low wind and fewer than 10 events in the catalog and (c) a typical winter day with severe weather, higher wind, and few or no events recorded in the catalog. Wind conditions were determined by examining the background microseisms in the continuous data for waveform characteristics and spectral frequencies consistent with wind. I examined multiple days throughout summer and winter until the conditions for the STA/LTA experiments were met. I specifically chose days with few or no earthquakes to determine if there were genuine changes in Gareloi’s seismic activity being able to overcome the STA/LTA threshold or if events were being masked by environmental noise, such as wind.

For the summer day, June 25th, 2016 (Figure 11A), I used a detection threshold of 1.85 and found 99 events which were not in the catalog. On a clear winter day, November 10th, 2017, (Figure 11B), I used a detection threshold of 1.85 and found 40 uncatalogued events. Lastly, on the windier winter day, November 8th, 2017, and also using a 1.85 detection threshold, there
were approximately 34 events among the background noise which were not in the catalog. With the STA/LTA from these 2-hour windows, the earthquake counts for these days increase by 93%, 85%, and 100% respectively, and if done on the entire day, the percentages for the clear summer and winter days would likely increase even further. If STA/LTA experiments were run on the 2008-2015 events, it is probable the counts would increase by similar percentages as well.

As mentioned previously, there were several instances of multiple events with different seismic signals contained in a single waveform file, many of which did not generate separate waveform files for the second event. These multiple events corroborate the continuous data findings that more events occurred at Gareloi than were detected or locatable. In order to remain consistent with the number of events hypoDD relocated and avoid confusion, waveform files which contained multiple events with differing seismic signals are considered separately, similar to how Unclassified seismic signals are considered separate. However, unlike the Unclassified seismic signals, I cannot discern which of the two events relocated, and as there are less than 150 occurrences of these instances, the total counts and hypocentral relocations for these multiple seismic signal events are not included below.

Because the earthquake counts consists of detected seismicity only (i.e. earthquakes recorded in the catalog), the following results focus primarily on observations made on those events.

**Total Counts**

**Overview of 2003-2019 Earthquakes**

Seismicity varied significantly between the three time periods, exhibiting differences in the total of detected and located earthquakes (Figure 13). The 2003-2007 subset saw the most earthquakes of all three time frames, as the network was in peak health. The 2008-2015 time period recorded the least number of located earthquakes, as there were numerous station outages during this period. Finally, the 2016-2019, right after the network was restored and before the instruments were upgraded, saw the second most detected and located events. In all cases,
however, the counts presented here almost certainly underestimate the true number of earthquakes on Gareloi.

2003-2007 Earthquakes

Earthquakes recorded between 2003-2007 comprise approximately 61% of the entire catalog with a total of 3,594 earthquakes (Figure 13). As seismometers were installed in October 2003, there are few earthquakes that were recorded for the year, with a total of 15 in the catalog. After 2003, higher numbers of events were detected (Figure 13). Throughout this time period, I observe annual increases in total seismicity, with an especially high increase in total counts from 2006-2007 (Figure 13). Seismicity in 2006 and 2007 alone totals 2,552 events, approximately 71% of 2004-2007 seismicity, representing about 43% of the total seismicity located on Gareloi. 2007 was the year that saw the highest annual count, with a total of 1,476 earthquakes (Figure 13). As such, 2007 seismicity represents approximately 25% of the total detected seismicity of the study.

During this time frame, the overwhelming majority of earthquakes had long period characteristics. Of the 3,594 earthquakes, 3,181 (89%) were LP events, compared to just 354 HF events or about 10% (Figure 14). Furthermore, the number of LP events saw a steady increase year to year from 2004-2007, while HF seismicity remained between 65-100 events per year (Figure 14). HF activity in the winter months was often located more commonly than LP events, as its impulsive P-waves are more likely to trigger the STA/LTA algorithm (Figure 11B).

2007 Earthquakes and Multiplets

Throughout the 16-year time span of this study, 2007 is the only year with significant multiplet activity. Composed entirely of LP seismicity, this repetitive seismicity occurred from April through July with several distinct phases.

A rapid increase in seismicity began in mid- to late-April 2007 and continued through early May, for a total of 681 earthquakes. Of these, approximately 208 waveforms were highly
similar with correlation coefficients >0.7 across stations GAEA, GALA, and GANE, the three most reliable stations of the study (Figure 15). Station GAEA was the most consistent and reliable, and was the primary station used for cross correlation (Figure 15).

After early May, the seismic activity decreased dramatically through the month of June 2007. During this time frame, only 162 earthquakes were located. These events do not show as many repeating earthquakes, with 37 events with correlation coefficients >0.7 (Figure 15).

Following this relative lull, a resurgence of LP activity around the northern half of the island began at the end of June and lasted through late July. July alone saw 356 earthquakes. Multiplet activity continued into July, with approximately 128 highly correlated events occurring in two clusters (Figure 15). In total, 1,199 earthquakes occurred between April through July 2007, of which 373, or 30%, were repeating earthquakes.

2008-2015 Earthquakes

The 2008-2015 time period poses the greatest uncertainty for this study. Over the course of these years, all six Gareloi stations experienced frequent outages (Figure 16), and events during this time period represent only 7% of the study’s total seismicity. With the exception of 2008, fewer than one hundred earthquakes were recorded per year (Figure 13). This is significantly different from what has been typically observed at Gareloi, and continuous data from IRIS demonstrate the located seismicity during this time frame are far below what is actually occurring (Figure 10).

Of the 413 seismic events recorded during this time frame, 379 events, or 92%, were HFs and 21, or 5%, were LPS. Compared to the previous subset and combined with the low number of LPS, this is a drastic increase in HF activity, which has clearer and better defined phase arrivals than LPS. However, as shown by the continuous data (Figure 10), LPS remain prominent but were not triggering as often as they had between 2003-2007, as they have emergent P-wave arrivals and often lack any, if at all, clear S-phase arrivals. It is possible that after 2007, the strength of LP events diminished and did not pass the triggering threshold as often. This may
also be the result of the station malfunctions, and there being an insufficient number of stations detecting the same earthquake to consider it a detected, and therefore locatable, event.

2016-2019 Earthquakes

Seismic activity between 2016-2019 accounts for the remaining 32% seismicity in this study, with a total of 1,877 located earthquakes (Figure 13). For the located events between 2016-2019, spectral analysis reveals 1,256, or 67% HF earthquakes, 524 or 28% LP earthquakes, and 26 earthquakes with waveforms and frequencies that are difficult to distinguish and thus that could not be classified with confidence (Figure 17).

Prior to the upgrade from short-period to broadband seismometers in July 2019, the number of events for this time frame are shown in Figure 13. As with the 2008-2015-time period, there is a significantly higher number of HF events compared to LPs, yet continuous data shows there is a clear abundance of low frequency events going undetected from 2016-2019 (Figure 11). However, unlike the 2008-2015-time period, the Gareloi network was in full health from 2016-2019, and after network restoration, there were no changes to AVO’s STA/LTA threshold at Gareloi (Power, personal communication, 2022). This suggests that a significant portion of Gareloi LP seismicity is not included in these data because these events again did not rise above the STA/LTA threshold as easily or as often as they did from 2003-2007. And due to these undetected events, the total seismicity on Gareloi between 2016-2019 is likely far greater than 1,877 events contained in the AVO catalog. Without the full waveform or phase data, it is difficult to determine how the total seismicity of the island changed.

Based Gareloi’s history of extremely high levels of background seismicity, I can speculate the true number of LP events between 2016-2019 may be much higher, potentially on the order of the located events of 2003-2007 (Figure 11). Regardless, there is a clear increase in the occurrence of HF events at and around Gareloi, where 67% of events from 2016-2019 were HF compared to just 10% from 2003-2007, (Figures 14 & 17).
**Apparent Earthquake Seasonality**

Monthly counts of Gareloi seismicity suggest a seasonal trend, with more events recorded between March and September compared to the number of events recorded between October and February (Figure 18). To investigate potential seasonal trends, I chose days between October and February, most often November, when few earthquakes appear in the AVO catalog. This was done to confirm if there were genuinely fewer earthquake during the colder months, or if they simply were not included in the catalog.

For these winter days, I examined 2-hour windows of continuous data at a time for days of low and high wind and/or other environmental noise, based on the spectral content of the continuous data. I then compared the number of detected events in the catalog to a general estimate of non-detected events displayed in the 2-hour data windows. Following this, I performed an STA/LTA on several days to acquire a more concrete number of non-detected events. The STA/LTA experiments were performed at several thresholds, and in all instances, there were far more events found in the continuous data than was recorded in the catalog.

After investigating recent continuous data (continuous data for Gareloi are only archived at IRIS for periods after 2008) for days in winter with low wind and a small number of detected events (<10) listed in the catalog, I discovered many smaller events (Figure 11) that appear in the continuous record but were not located. This suggests that severe winter weather conditions masks smaller events that cannot rise above the environmental noise (wind and surf) to trigger the network’s STA/LTA algorithm. Given its locality, harsh winters with sub-freezing temperatures, heavy snowfall, and severe winds are common at Gareloi (Buurman et al., 2014). Consequently, seismic activity is likely buried within environmental noise and causes the appearance of less seismicity during periods of poor weather (Figure 11B). I must note this is an extrapolation for the 2003-2007 timeframe from the continuous data of the latter two time periods of the study as continuous waveform data was not available until 2008.

I then looked at days in the catalog when at least a dozen located earthquakes were listed, regardless of season, to compare the total number detected and non-detected events to examine how many events were going “unseen”, particularly in the latter half time periods of the study (2008-2015 and 2016-2019). This was done to confirm if the if there were genuinely fewer
events after 2007 or if this was the result of a change in the earthquake’s ability to rise past the STA/LTA threshold used by the Gareloi stations.

Following this, I began to compare the number of detected seismic events to wind speed measurements to further examine the potential relationship between the two. Unfortunately, no meteorological station resides on Gareloi, with the closest one located on Adak, ~150 km to the east. When I compared the average wind speed for a particular day at Adak to the spectrogram of the same day at Gareloi, the wind activity between the two islands were inconsistent with one another. Additionally, the Adak wind speed and number of Gareloi events did not correlate well. I then searched for archived weather forecasts for the western Aleutians, but I was unable to find these data as well. As such, I was unable to complete this experiment, and the relationship between number of detected events on Gareloi to daily wind speed and weather remains inconclusive.

**Hypocenter Relocations**

*Overview of 2003-2019 Earthquakes*

Overall, relocated hypocenters do not shift drastically from initial locations (Figure 19), and while slightly different, they are comparable to those calculated by Hypoellipse (2003-2012) and Hypoinverse (2012-present).

In general, relocations of Gareloi earthquakes form a generally more vertical shape beneath the island (Figure 19). Both initial and relocated hypocenters show a deepening of seismicity between 2003-2007 and 2016-2019 with no change in epicentral location. In map view, there are two distinct trends: early years display a faint NNW elongation angled toward the northern end of the island, while the later years display a clear W-NE trend across the island, clustered near the west flank and tapering toward the northeast (Figure 19).

More HF events occur in the 2016-2019 subset compared to the 2003-2007 subset (Figure 20). Due to numerous LP events going undetected in the 2016-2019 subset (see Figure 11A), I cannot directly comment on whether all LP seismicity also experienced a shift in hypocentral locations. Further, due to the absence of continuous data before 2008, I also cannot
confidently report on whether or not the percentage of undetected LPs from 2003-2007 are of comparable levels to those seen in 2008-2015 and 2016-2019.

Overall, Gareloi seismicity appears to have deepened over time (Figures 19 & 20). The majority of LP events tend to occur at shallower hypocentral depths of 2-10 kilometers while the majority of HF events fall between 6-20 kilometers with scattered events at shallower depth. (Figure 20).

LP seismicity appears to become more scattered after 2007, but generally relocates in proximity to initial locations (Figure 20). While HF activity also does not shift far from initial locations, the range of locations in cross section is greater than that of LP events (Figure 20). LP activity seems to locate most often with a very slight NNW elongation across the island (Figures 19B & 19C), but the overall area of seismicity encompasses a significant portion of the island. HF seismicity, on the other hand, most often centers around the north half of the island with a more W-NE trend (Figure 20).

2003-2007 Earthquakes

For this early time frame, hypocenters are fairly shallow, and relocations occur in a similar spatial distribution as initial locations. In this subset, depths ranged between 2 and 10 kilometers in a narrow vertical distribution beneath the island (Figure 21).

During this time period, 89% of Gareloi seismicity were LP signals with an overall depth distribution between 2 and 10 km, though there are a few instances of LP events with depths as deep as 15 km. In contrast, the HF signals occurred in scattered locations throughout the edifice (Figure 22) and depths from 1 to 20 km. LPs appear to relocate in close spatial proximity to their initial hypocenters but tighten slightly beneath the island. Meanwhile HFs seem to have relocated slightly further from initial locations, moving toward the island and collapsing into much narrower locations than LPs (Figure 22C).

Relocated epicenters occur primarily on the northern flank of the island (Figures 21C & 22C), with a faint NNW orientation. At current resolution, it is difficult to interpret if these
events originate at North Peak or merely occur in close spatial proximity beneath its north-northwestern flank and concentrate beneath the northern part of the island.

2007 Earthquakes and Multiplets

The 2007 multiplet earthquakes are composed entirely of LPs and occur in a tightly confined area 1-8 km depth beneath North Peak (Figure 23). Relocations align in a tight conduit-like shape beneath the island between 1 and 10 km depth (Figure 23).

A standard assumption is that highly similar earthquakes cluster together within a quarter of a wavelength (Geller & Mueller, 1980). Relocated depths for the 2007 multiplets, however, stretch over several kilometers (Figure 23) although they are tightly clustered in map view. I propose this apparent range of depths is not real and is due to the relative lack of S-waves, leaving depths poorly constrained.

Hypocenter relocation using both catalog and cross correlated arrival times places the multiplet beneath North Peak with a northwest trend (Figure 23). In April and May, there appear to be two distinct multiplets occurring simultaneously (Figure 15) within the same region. In contrast, June hypocenters display more scatter across the island, at a slightly smaller range of depths, between 4 and 8 km (Figure 23).

The July resurgence differs from the activity in April and May in that July events are much more similar and cluster in a tighter conduit-like shape beneath the island compared to those clusters occurring in April/May and June (Figures 23). While early through mid-July events strongly resemble those in the June cluster, earthquakes in late July share characteristics with both the April-May and June sequences (Figure 15).

2008-2015 Earthquakes

With so relatively few located events and such poor station health, earthquakes recorded between 2008 to 2015 do not locate well in hypoDD (Figure 24). As such, I lowered my minimum number of observations per event pair to 4 for a broader scale seismicity. Hypocenters
relocate differently than those of 2003-2007 subset. Events at Gareloi’s west flank tighten significantly, and many of the earthquakes 8 km and deeper either also shift substantially or disappear entirely. Most of the events of this time frame occur to the region west of Gareloi at depths > 6 km (Figure 24).

2016-2019 Earthquakes

Overall, Gareloi seismicity from 2016-2019 appears different from the 2003-2007 time period. Relocated hypocenters tighten only slightly beneath the island around where 2003-2007 events occurred, but 2016-2019 seismicity does not cluster and is far more scattered than 2003-2007 earthquakes (Figures 25 & 26). Seismicity from this time frame also display overall deeper hypocenters, falling between 6-16 kilometers compared to the 2-10 kilometer depths in the 2003-2007 subset (Figures 25 & 26).

Along with this apparent deepening of hypocenters, there is also a shift in epicentral locations. While 2003-2007 seismicity predominately occurs beneath the northern half of the island (Figures 20 & 21), 2016-2019 seismicity occurs beneath the northern half of the island, oriented in a west-northeast trend, with a greater number of events to the west (Figures 25 & 26). There is also an overall increase in regional seismicity when compared to the earlier years of the study. In particular, on May 8, 2017, there was a M6.2 earthquake between Gareloi and Tanaga Islands, which produced a significant aftershock sequence (https://earthquake.usgs.gov/earthquakes/eventpage/us10008qhu/executive), but as these events are regional, they are not related to the geophysical processes occurring on and within Gareloi.
Discussion

Mount Gareloi seismicity is unusual among other volcanoes throughout Alaska and the world, and developing a model to explain its unique seismicity is crucial to understanding its magmatic system. The Gareloi model must strive to explain (a) the constant not-eruptive seismicity, (b) the predominantly LP nature of activity during the early years of the study which then morphs into containing more HF events during the latter years of the study, (c) the broad absence of multiplet activity and the possible mechanism(s) which instigated the sudden and brief appearance of multiplet activity from April-July 2007, and (d) the broad range of hypocentral locations beneath the island. To develop such a model to explain Gareloi seismicity, I consider the geophysical process(es) for each of these characteristics in the following paragraphs.

Interpretations of Gareloi Seismicity

Changes of 2003-2019 Earthquake Rate and Signal Types

Over this 16-year study period, Gareloi Volcano demonstrates apparent transitions in types and degree of seismicity. LP seismicity dominates the majority of the 2003-2019 earthquakes on the island. Additionally, I have confirmed that compared to HF earthquakes, LP events in the 2003-2019 timeframe have the broadest distribution of the overall seismicity and include the best re-located earthquakes of the study (Figure 20C). Throughout the entirety of the study, low-frequency earthquakes likely driven by volcanic fluids (magma or gases and water heated by magma) appear to initiate seismicity almost constantly. High-frequency earthquakes, possibly originating from shear slip and block rotation also contribute to Gareloi seismicity (Figure 20C) with increasing totals between the study’s subsets (2003-2007 and 2016-2019).

From 2003-2007, several processes may be responsible for fluid-generated earthquakes at Gareloi, such as volcanic fluids, or seawater and meteoric water percolating into the edifice,
heating up, and converting into steam, or a combination of all three. Any combination of these likely initiated nearly all earthquakes on Gareloi in this time period, as activity occurred between 1-10km depth below sea level, consistent with typical depths of LP seismicity (Chouet, 1996; McNutt, 2002; Power et al., 2004; Caplan-Auerbach & Prejean, 2005; White & McCausland, 2019; Figures 20C, 22C, 23C, & 26C). The total number of LPs increased from year to year culminating in the high rate of seismicity in 2007 (Figure 14); this may have been the result of an injection of new magma into the system. Without a clearer image of where Gareloi’s magma reservoir lies, however, this remains speculative.

Between 2003-2007, HF seismicity on Gareloi occurred in two well-defined areas with the cross section (Figure 22). These linear features indicate a possibility of diking within the system, which resulted in these brittle failures. Throughout 2003-2007, many instances of HF activity appear to occur in short-lived swarms that occur. The most prominent of these potential swarm activities is from October 5, 2004, where a total of 25 HF events occurred over the course of an hour; out of all years in the 2003-2007 time period, 2004 and 2005 experienced the most HF activity (Figure 14). Additionally, nearly all HF activity in this time period occurs in these two linear features (Figure 22), and the relocated HF seismicity tightens significantly from initial locations. As this seismicity repeatedly occurred in the same areas within the edifice, this may suggest the gradual onset of diking over several years, with 2004 and 2005 experiencing the strongest activity. These probable dike intrusions may have acted as potential catalysts for the 2007 multiplet activity as HF activity occurred at the start of April, right before the uptick in seismicity and emergence of multiplets occurred. Though this remains speculative, these linear features may have opened new pathways for volcanic fluids to travel, as the area of multiplet activity strongly coincides with the centermost area of HF activity (Figures 22 & 23).

Due to the frequent outages and overall poor station health, data from 2008-2015 presents a sizeable gap in the ability to track seismicity (Figures 16 & 24C) and in understanding the dominant geophysical processes on Gareloi during this time period. From continuous data recorded at single stations, it is known LP activity still occurred frequently, with dozens of earthquakes in a two-hour data window (Figure 10B). I speculate that fluids remained a steady source of seismicity on the island throughout these years (Figure 10B). Additionally, a large
portion of the HF seismicity recorded during this time period occurred to the west of Gareloi but is generally not associated with the volcano itself.

Seismicity in 2016-2019 has a higher rate of HF activity relative to the start of the study period (Figures 14 & 17). Part of this increase results from moderate to large magnitude earthquakes occurring regionally, such as the cluster occurring in May 2017 after a M6.2 between Gareloi and Tanaga (https://earthquake.usgs.gov/earthquakes/eventpage/us10008qhu/executive; Figures 25 & 26). Further, these regional earthquakes between Gareloi and Tanaga cluster in a north-south orientation, approximately along the edge of the proposed northern boundary of the Delarof block (Geist et al., 1988; Ruppert et al., 2012). This is consistent with the results of Lally (2019) for earthquakes offshore of Tanaga.

HF events directly beneath Gareloi relocate strongly in an W-NE trend across the northern half of the island between 4-12 km depth (Figure 26C), which is also subparallel to the top boundary of the Delarof forearc block. These could stem from brittle fractures or cracking in the edifice (Chouet, 1996), as the below-sea-level depths of these events are likely too deep to be a structural fault within the ~1,600m high volcano (Figures 25C & 26C), but these could be related to stresses related to rotation of the Delarof block. As the proposed boundaries for the forearc blocks are not clearly defined, it is possible the edge of the Delarof block bisects Gareloi Island rather than merely being subparallel to Gareloi’s HF seismicity.

Overall, HF activity does not tighten into linear features associated with dike intrusions, but poor depth constraint hampers conclusive interpretations of their cause (Figures 25C & 26C). These relatively scattered events may be showing possible weak zones throughout Gareloi’s young edifice (Figure 27) responding to regional or magmatic-induced stresses and failing in this brittle manner. This may indicate the volcano is composed of heterogenous, unconsolidated, and highly fractured material (Figure 27). HF activity occurs in relatively the same area in map and cross section views throughout the study (Figures 22C & 26C). Given the W-NE trend of these events also coincides in the vicinity of the original slip surface of known debris flow areas (Coombs et al., 2007), these features may contribute to the increased HF activity. Based on the presence of these debris flows and history of flank collapses, it is not out of the realm of possibility these areas may fail again (Figure 8; Coombs et al., 2007).
LP events during the 2016-2019 timeframe remain steady throughout the time period (Figure 11A) and at depths of 4-16 km beneath the volcano (Figures 26B & 26C), indicating volcanic fluids remain a constant contributor to seismicity in this time frame as well, but to a lesser extent and less strength to trigger the STA/LTA threshold than in the first part of the study.

**Hypocentral Relocation Dissimilarity and 2007 Multiplets**

A distinguishing feature of Gareloi earthquakes is that normal, background seismicity consists of dispersed, dissimilar events. Events do not strongly correlate or cluster tightly in a single area and consistent depth (Figures 19C-22C, & 24C-26C). Instead, seismicity occurs over a large area broadly toward the northern part of the island with a wide range of depths regardless of seismic signal (Figures 20C, 22C, & 26C). These non-repeating events indicate that there are many sources within a fractured, heterogeneous system without common faults or repeating sources. These sources may originate from fluids, like seawater or meteoric water pervading into the system from different locations in the edifice and being heated by the magma and moving through the fractured edifice (Chouet, 1996; Figure 27) and the exsolution of gas within the magmatic system (Chouet, 1996; McNutt, 2002). Fischer et al. (2021) report that Gareloi gas emissions from fumaroles have the most magmatic gas compositions (along with Kiska), the highest gas temperatures, and highest SO$_2$ emissions of all Western Aleutian volcanoes sampled in their study, which is a potential indicator the gases have had little interaction with Gareloi’s hydrothermal system (Giggenbach, 1996). This magmatic gas composition and the release of volatiles specific to a magmatic system rather than hydrothermal or mixed magmatic-hydrothermal could be a potential factor in explaining the island’s abundant seismicity, and in particular, LP earthquakes. This could also help constrain and characterize the location and size of Gareloi’s magma reservoir.

However, the measurements from Fischer et al. (2021) were taken from South Peak fumaroles, and very little seismicity is observed beneath the southern end of the island. This lack of earthquakes at Gareloi’s southern half implies that the magmatic system resides below the north end of the island, where the vast majority of seismicity is relocated and thus, the South Peak is not a significant source of deep earthquakes. Because hypoDD discards earthquakes...
above sea level, I cannot discern how seismicity associated with the fumaroles dotting the flanks of South Peak contribute to Gareloi’s total seismicity. As such, further work is necessary in order to investigate this potential relationship between degassing of magmatic-composition gases and extremely high levels of background seismicity.

Because Gareloi earthquakes are dominantly dissimilar, the 2007 multiplets are a deviation from typical Gareloi behavior. These repeating events may represent an injection of new magma into the reservoir beneath the 20 km demarcation shown in Figure 27, as repetitive seismicity has been postulated as a final stage of seismicity before eruption (White & McCausland, 2019). White and McCausland (2019) suggest that multiplet seismicity in the final stages before eruption takes places at around 2 km, but depths are poorly constrained for Gareloi earthquakes, and the evidence of the location of Gareloi’s magma reservoir resides remains unclear.

A recharge of material into a magma reservoir or a compositionally new material being fed into the magmatic system would have brought new gases into the reservoir. As previously mentioned, fumaroles at Gareloi have been found to be magmatic in composition; an increase in these volatiles may have increased degassing within the system and led to the multiplets. Injections of magma into the reservoir have been found to be associated with deep long-period (DLP) seismicity between 10-45 km at other volcanoes throughout Alaska and the Aleutians (Power et al., 2004). No DLP were located beneath Gareloi during the time period of this study or in the aforementioned 2004 study, however. As such, this theory, combined with the ambiguity of Gareloi’s magma reservoir location and uncertainty of gas emissions of magmatic composition as it relates to seismic activity and earthquake locations, is difficult to establish.

Alternatively, the LP nature of the multiplet seismicity may indicate sustained fluid motion through a single fracture or conduit. Another possible explanation within this is the volcanic fluids may have flowed through the same cracks(s) in the fractured edifice (Figure 27) repeatedly from April through July 2007 or a repetition of gas bubble exsolution in a localized area or fracture. It is possible that a fracture formed somewhere outside the magma reservoir and ductile zone and created a new pathway for gas release from the magmatic or hydrothermal systems, thus instigating the LP seismicity (Chouet, 1996).
Based on the strongly linear features where HF activity occurred from 2003-2007, it is possible diking took place gradually in Mount Gareloi’s interior, which could have led to a change in the dominant pathway for gas or fluid release. However, as HF activity before the onset of increased in LP seismicity and occurrence of the 2007 multiplets in approximately the same area as Gareloi’s HF events, it remains possible the April-July 2007 multiplet activity was a failed eruptive event. This new conduit for fluid movement may not have been an open enough system to allow for fluids to reach the surface for an eruption. Because the multiplets had a correlation coefficient of 0.7, it also remains possible the fluids repeatedly flowing through the fracture were not strong enough to trigger a full-scale eruption.

Multiplets could have occurred as the result of pre-existing igneous bodies repeatedly failing, but if this were the case, the multiplets would have exhibited HF seismicity rather than LP (Chouet, 1996). As such, I interpret the multiplets as originating from heated fluids moving through the same fracture or area, possibly a resulting feature from previous diking, within a highly fractured edifice (Figure 27).

**Forecasting Eruptions at Gareloi**

Given the persistent LP nature of Gareloi seismicity and the lack of instrumentation to record its most recent, confirmed eruption (1989; Table 1), forecasting eruptive events at this particular volcano poses a significant challenge. The levels of background LP seismicity at Gareloi have preceded eruptions at other volcanoes, such as Pinatubo in 1991 (Harlow et al., 1996; White, 1996; White & McCausland, 2016; White & McCausland, 2019), Asama volcano in Japan in 1958 and 1983 (Chouet, 1996), El Chichón in 1982 (Chouet, 1996), dome growth of Soufriere Hills Volcano, Montserrat in the 1990s (Miller et al., 1994), Mount St. Helens in 1980 (White & McCausland, 2019), Augustine Volcano in 2006 (White & McCausland, 2019), and Galeras Volcano in Colombia in 1993 (Fischer et al., 1994). Because these extremely high levels are normal for Gareloi, its “normal” cannot be easily compared with that of other volcanoes.

Should Gareloi’s already-high levels of seismicity increase, however, then these typical precursors could be used as potential indicators that this volcano is undergoing a change and may be building toward eruption. These increases in seismicity could be a general increase in the
occurrence rate of daily events, which would raise the background levels above Gareloi’s normal. As the majority of Gareloi earthquakes are very low magnitude, mostly below M2 (Figure 28), increases in size of event magnitude would also be a deviation from background levels and could be a potential indicator of changes happening in the system. Changes in signal type, transitioning from predominantly LP to HF seismicity could be another precursor indicative of a change in the magmatic system, and potentially impending eruptivity. Finally, the onset of seismic tremor could be indicative of unrest.

Of all increases, however, the factor which may likely have the greatest impact on whether an eruption is imminent or not is the presence of multiplets, which would indicate a persistently active source rather than activity in a distributed system. Throughout the 16 years of the study, there was only one instance of highly correlated multiplets. Changes in earthquake similarity from dissimilar events to suddenly highly correlated events, particularly of LP events, would be indicative of a new and persistent source process, potentially stemming from the injection of new material, or a change in the dominant fluid.

Finally, as Gareloi’s location beneath a heavily traveled air corridor, having an indicator(s) of a possible or imminent eruption is extremely important for air travel safety (Coombs et al., 2008). With the nearest population center and airport ~150km away, without a reliable forecasting method for the volcano, it would be impossible for aircraft to make emergency landings in this area. Thus, being able to better forecast eruptions at Gareloi—and by extension, other volcanoes—is essential to aviation safety and avoiding disaster (Guffanti et al., 2010).

2021 Activity

In May 2021, in the final stages of this research, Gareloi experienced an increase in background seismicity. In addition, the earthquakes displayed multiplet behavior with correlation coefficients of 0.9 and above (Caplan-Auerbach, personal communication, 2021). By comparison, the April-July 2007 multiplet activity has average correlation coefficients of 0.7. As a result of this elevated seismic activity with multiplets, AVO raised the Alert Level to Advisory and Color Code to Yellow for Gareloi until July 28th when seismicity and multiplet activity
diminished and returned to Alert Level to Normal and Color Code to Green respectively.

Conclusion

After the relocation of the 5,884 earthquakes from 2003-2019, I find:

1) Gareloi earthquake hypocenters are broadly distributed across the island, slightly concentrated more on the north half of the island, and with few instances of earthquake hypocenters clustering in a single place. Instead, there is a large range of hypocentral depths, and many relocated hypocenters are scattered throughout the island and region.

2) Gareloi earthquake waveforms are broadly dissimilar, indicating multiple sources of seismicity throughout the island, and lends to the possibility of a highly fractured, heterogeneous edifice in which seismicity originates.

3) Gareloi seismicity is predominantly composed of non-repeating LP events, also an indication of multiple sources throughout the island. Although I cannot definitively identify the sources, possibilities for sources include: fluid movement throughout abundant fractures in the volcano’s edifice, constant exsolution of gas out of magmatic and/or hydrothermal systems, and interactions of fluids within system which originate from the heating of gas or water by the magmatic system.

4) HF seismicity can be attributed to brittle failures within Gareloi itself and regional seismicity. Areas of possible diking and the edifice’s unconsolidated, likely fractured, heterogeneous structure are probable sources for the HF activity to accommodate magmatically-induced stresses. The centralized location for early HF earthquakes aid in constraining that a likely location for Gareloi’s magma reservoir may be more centralized around the northern half of the island, but this is not definitive, as all relocations are relative and activity below 20 km in cross sections remain uncertain. Meanwhile accommodation of high-rate and oblique angle subduction by the Delarof block explain seismicity offshore from Gareloi. As the boundaries for the proposed block rotation are not well defined and based on the orientation of Gareloi’s HF
seismicity, it is possible the boundaries of the Delarof block may “cut through” the island along this line, instead of simply being subparallel to the seismicity, and be the potential source of HF activity.

5) The only instance of multiplet activity was from April-July 2007, all of which exhibited LP seismicity. I propose this was the result of the repeated movement of heated fluids through a localized fracture, possibly related to an injection of new, gas-rich magma into Gareloi’s reservoir. This may have initiated the start of an unrest, but the system settled before the culmination of an eruption. However, with a lack of DLPs, which have been associated with magma recharge at other Alaska volcanoes, it remains uncertain if the 2007 multiplets truly resulted from one or more recharge events.

6) From 2003-2007, there were vastly more LP events compared to HF within the AVO earthquake catalog; however, from 2016-2019, HF hypocenters dominated the catalog. Visual inspection of continuous data suggests that while the true rate of LP seismicity appears unchanged, most LPs in this latter time frame lacked the strength to surpass the STA/LTA to be detected by seismometers and therefore be able to be located.

7) Many small events were undetected by the STA/LTA used by AVO to track earthquake activity at Gareloi. Typically, these events were too small to be located and were not considered in this analysis. These events can be found in continuous data, such as those shown in Figures 10 & 11.

8) Emergent P-waves and absent S-waves in LP seismicity result in poor hypocentral constraint, particularly regarding depths, and represent a significant source of uncertainty for relocated hypocenters. Meanwhile, the better defined P- and S-waves of HF seismicity allowed for a much tighter, smaller range of hypocentral locations and depth compared to LP events. However, there still remains uncertainty in HF locations, as hypoDD locations are relative and there are fewer HF data when compared to LPs.
9) Fewer earthquakes are recorded in winter months compared to summer months (Figure 18), but this is the result of severe weather (wind and surf) interfering with seismometers and burying earthquakes in environmental noise. Gareloi likely experiences a similar number of earthquakes in winter as it does summer.

Mount Gareloi’s exhibition of extremely high levels of background seismic activity provides insights to the island’s geophysical processes; however, further studies on Gareloi’s surface and interior are needed to better understand and define the processes and sources instigating of the island’s constant seismicity.
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Tables and Figures

Figure 1. Location of Gareloi (black circle) relative to other historically active volcanoes in Alaska and the Aleutian Arc. Slightly modified from Coombs et al., 2008. Mount Gareloi is one of westernmost islands in the Aleutian arc, and therefore, one of the most remote. It is 150 km from Adak, the nearest population center, and ~2000 km from Anchorage. Both cities have been denoted in black.
Table 1. From *Coombs et al., 2008* and collected by C. Cameron. Observation and record of volcanic activity at Gareloi Volcano, Aleutian Islands, Alaska.
Figure 2. Map and east-west cross section of total seismicity located on and around Gareloi Volcano from 2003-2019, using initial hypocenters, as located by AVO. White outlines mark approximate boundaries of Gareloi, Kavalga, Ogliuga, and Skagul Islands. White diamonds represent locations of Gareloi seismometers. Years are represented by the color scale, where purple to blue circles represent the early years of the study (2003-2019), lighter blue to green circles represent the second part of the study (2008-2015), and yellow, orange, and red circles represent the last third of the study (2016-2019).
Figure 3. Helicorder of a typical two days of seismic activity recorded at station GAEA. Each increase in amplitude within the helicorder data represents a single earthquake, demonstrating the extremely high levels of background seismicity which occur on the island every day. The thick, rectangular blue lines at hours ~07:48:00 and ~19:48:00 on both days represent calibration pulses, not seismic activity. Provided by Jackie Caplan-Auerbach.
Figure 4: Examples of typical waveform signals and spectrograms found at Gareloi, taken during the 2003-2007 time frame. 4A) depicts the waveforms and spectrograms we associated with LP seismicity, earthquakes with peak frequencies between 1-5 Hz, emergent P-waves, and lack of clear S-waves. 4B) illustrates the waveforms and seismograms we classified as HF seismicity, earthquakes with peak frequencies >5 Hz, and clear P- and S-waves.
Figure 5. From Ruppert et al., 2012. Schematic representation of tectonic context of crustal strike-slip earthquakes in the central Aleutian Arc. Locations of crustal blocks, sedimentary basins and selected volcanoes are indicated. The features are not to scale. Mount Gareloi resides within the Delarof Block.
Figure 6. Courtesy of Jones, 2013. Close up of Mount Garelohi, looking from the South toward North. Both North and South Peaks have been volcanically active; the primary vent is thought to be North Peak and active fumaroles appear more abundant in the South Peak (Coombs et al, 2008).
Figure 7. From Coombs et al., 2008. Geologic map of Gareloi Island, Aleutian Islands, Alaska.
Figure 8. From Coombs et al., 2007. GLORIA side-scan image (A) and topography and bathymetry (B) of Gareloi volcano, detailing area and extend of prior debris avalanche flows from the volcano.
Figure 9. From Coombs et al., 2008. Map of Gareloi seismic network. Stations GASW, GANO, GANE, GAEA, and GALA reside on Gareloi itself, and station GAKI is located on Kavalga Island.
Figure 10A: Example of continuous data from the 2008-2015 subset on station GAEA, which display more seismicity occurred on the island than was locatable. In the catalog for August 1st, 2010, only six events are recorded, but this continuous data from 12:00 to 14:00 shows there are close to 36 earthquakes in two-hour time window, including five of the six events recorded for this day. Continuous data accessed through the IRIS database.

Figure 10B: Example of continuous data from the 2008-2015 subset on station GAEA, which displays abundance of LP seismicity that was not recorded during this time frame due to station health and/or changes in triggering algorithm threshold. On July 7th, 2011, there no earthquakes are recorded in the catalog, either LP or HF, but these two hours of continuous data from 16:00-18:00 show dozens of earthquakes with the majority being LP seismicity. Continuous data accessed through IRIS database.
Figure 11A: Example of continuous data from the 2016-2019 subset which shows abundance of seismicity found on station GAEA. During June 25th, 2016, only seven events are recorded in the catalog with the majority of the activity displaying HF seismicity. This two-hour window of Careloi seismicity from 08:15 to 10:15 displays far more seismic activity than is recorded in the catalog, but because none of the events in this two-hour window surpassed the STA/LTA triggering threshold or were not seen clearly on other stations, they were not locatable by AVO analysts. As such, there are more events in the continuous record than the catalog. The continuous data also reveals there was a significant number of LP events in addition to the HF earthquakes on this day. This is one consequence of the change in triggering algorithm after 2015. Continuous data accessed through IRIS database.
Figure 11B: Examples of continuous data from the 2016-2019 subset which shows abundance of seismicity during a day of low wind in winter. On November 10th, 2017, there are only seven events recorded in the catalog, primarily displaying HF seismicity. Only one catalog event occurred during this two-hour time frame. This two-hour window of Gareloi seismicity from 04:00 to 06:00 clearly displays dozens of earthquakes which not recorded in the catalog and therefore, not located by AVO analysts. Throughout the study, there are generally fewer located earthquakes in winter months than summer months, but the number of earthquakes during these two-hour windows on this low-wind day imply that the apparent lack of winter seismicity is the result of harsh winter conditions, such as wind, masking seismicity by making it difficult for Gareloi’s small magnitude earthquakes to overcome the STA/LTA threshold and indicate there has been an earthquake and be located by AVO analysts. The clearer, stronger signals given by HF earthquakes are more easily discerned by the naked eye than LP events. HF activity, as it’s often tectonic in nature, has an easier time rising above the wind noise and triggering threshold, and as a result, most of the events found during the winter months display HF frequencies and waveforms. Despite this apparent masking, seismicity on and around Gareloi during winter remains steady and displays similar levels as seismic activity as summer months.
Figure 12. Map and east-west cross section of Garelo station health, using total relocated seismicity located on and around Garelo Volcano from 2003-2019. All relocations use catalog data only, for broader scope of seismicity and station health. White outlines mark approximate boundaries of Garelo, Kavalga, Ogluga, and Skagul Islands. White diamonds represent locations of the six Garelo seismometers. 12A) Relocated seismicity when all six Garelo seismometers are present in the station list for hypocenter relocation. 12B) Relocated seismicity when station GAEA is absent from the station list during relocation. 12C) Relocated seismicity when station GAKI is absent from the station list during relocation. 12D) Relocated seismicity when station GALA is absent from the station list during relocation.

Years are represented by the color scale, where purple to blue circles represent the early years of the study (2003-2019), lighter blue to green circles represent the second part of the study (2008-2015), and yellow, orange, and red circles represent the last third of the study (2016-2019).
Figure 12 (cont.). Map and east-west cross section of Gareloi station health, using total relocated seismicity located on and around Gareloi Volcano from 2003-2019. All relocations use catalog data only, for broader scope of seismicity and station health. White outlines mark approximate boundaries of Gareloi, Kavalga, Oglia, and Skagul Islands. White diamonds represent locations of the six Gareloi seismometers. 12E) Relocated seismicity when station GANE is absent from the station list during relocation. 12F) Relocated seismicity when station GANO is absent from the station list during relocation. 12G) Relocated seismicity when station GASW is absent from the station list during relocation.

Years are represented by the color scale, where purple to blue circles represent the early years of the study (2003-2019), lighter blue to green circles represent the second part of the study (2008-2015), and yellow, orange, and red circles represent the last third of the study (2016-2019).
Figure 13: Annual histogram of total seismic activity seen each year at Gareloi Island. The 2003-2007 are labeled in green, 2008-2015 in blue, and 2016-2019 in orange. There is a clear increase in the total seismicity from 2003 to 2007, which then drops dramatically from 2008-2015 due to poor station health and frequent outages. Following network restorage, total seismicity begins to increase again. Data for 2019 ceases temporarily as AVO scientists upgrade Gareloi seismometers from short-period to broadband instruments; although data resumes, we did not use this data.
Figure 14. Histogram for 2003-2007 data, individual years color coded. This displays a comparison of LP signals to HF signals during this time frame. Because weather appears to mask the winter events, there is highly likely that the true number of events, in particular LP seismicity, is much higher.
Figure 15. Correlogram of April-July 2007 multiplets. There are approximately 373 earthquakes which occurred during this time period which have a correlation coefficient of 0.7 or higher, separated into 5 clusters, plotted temporally. Events from April through May are more strongly correlated with events in late July while the few events from June more similar to earthquakes in the beginning of July. And events from early July are bear a strong resemblance to the events from Jane and mid-July. Events of late July appear to show similarities to Cluster 1 in the April-May sequence and the brief June activity. Catalog data shows that during April, 347 earthquakes occurred, primarily at the end of the month; in May, there were 334; June had 162 events; and July experienced 356 events. All repeating earthquakes display LP seismicity. Created using the Gismo Suite for MATLAB, (Thompson & Reyes, 2018).
Figure 16. Example of waveform and spectrogram of seismicity from 2008-2015, clearly exhibiting poor station health and outages of multiple stations at once.
Figure 17. Histograms for 2016-2019 data, individual years color coded. This displays a comparison of LP signals to HF and unclassified signals during this time. Because weather appears to mask the winter events, there is the likelihood that the true number of events, in particular LP seismicity, is actually higher. Unclassified signals were those which displayed waveform and spectrograms without clear waveforms and frequencies to indicate whether it was LP, HF, or some other volcanic-type seismic signal.
Figure 18. Histogram for all Gareloi data from 2003-2019 based on monthly earthquake totals and color-coded by individual year. While the chart implies more earthquakes occurred in warmer months (April-September) compared to colder months (October-March), analysis of recent continuous data (Figures 3 & 11B) indicates it is more likely events are being “masked” by the severe weather conditions Gareloi is subjected to, and therefore, this does not show accurately show the true number of winter events.
Figure 19. Map and east-west cross section of total seismicity located on and around Gareloi Volcano from 2003-2019, using GMT. White outlines mark approximate boundaries of Gareloi, Kavalga, Ogluga, and Skagul Islands. White diamonds represent locations of Gareloi seismometers.

19A) Initial hypocenters, as located by AVO. 19B) Relocated hypocenters using catalog-only data in hypoDD. 19C) Relocated hypocenters using both catalog and cross-correlated data in hypoDD. The blue oval denotes the faint N-NW elongation of 2003-2007 seismicity on the map and cross section in 19B and 19C. The orange ovals denote the approximate W-NE trend of 2016-2019 seismicity in the maps of 19B and 19C and cross section in 19B; relocations using catalog and cross-correlated data show there is less reliability in the relocations of 2016-2019 events and thus do not appear as clearly in the cross section of 19C.

Years are represented by the color scale, where purple to blue circles represent the early years of the study (2003-2019), lighter blue to green circles represent the second part of the study (2008-2015), and yellow, orange, and red circles represent the last third of the study (2016-2019).
Figure 20. Map and east-west cross section of total seismicity located on and around Gareloi Volcano from 2003-2019, labeled by signal type (LP vs. HF) over time. White outlines mark approximate boundaries of Gareloi, Kavalga, Ogliga, and Skagul Islands. White diamonds represent locations of Gareloi seismometers.

20A) Initial hypocenters, as located by AVO. 20B) Relocated hypocenters using catalog-only data in hypoDD. The red ovals on the map and cross section in 20B and 20C denote the area where the vast majority of 2003-2007 LP seismicity and a portion of 2016-2019 LP seismicity occurred. While there is a faint N-NW elongation to the LP seismicity, many events also occur outside of this area. The light blue ovals in the maps and cross section of 20B and map of 20C denotes the location where the majority of both 2003-2007 and 2016-2019 HF seismicity initiated; in particular, the 2016-2019 HF seismicity strongly displays an approximate W-NE trend, which is also subparallel to the boundary of the Delorof forearc block. Note that relocations using catalog and cross-correlated data heavily favor LP seismicity over HF; as a result, the W-NE trend of 2016-2019 HF earthquakes is less obvious in 20C, also corresponding to the less certain relocations of 2016-2019 events.

Years are represented by the color scales, divided between LP and HF seismicity. Dark red to pale yellow circles represent LP seismicity from 2003-2019, where dark red circles are the early years of the study (2003-2007), light red to light orange circles represent the middle years of the study (2008-2015), and pale orange to light yellow circles represent the last third of the study (2016-2019). Purple to pale blue circles represent HF seismicity from 2003-2019, where purple to dark blue circles are the early years of the study (2003-2007), dark blue to light blue circles represent the middle years of the study (2008-2015), and light blue to pale blue represent the last third of the study (2016-2019).
Figure 21. Map and east-west cross section of seismicity located on and around Gareloi Volcano from 2003-2007, using GMT. White outline marks approximate boundary of Gareloi Island. White diamonds represent locations of Gareloi seismometers. 21(A) Initial hypocenters, as located by AVO. 21(B) Relocated hypocenters using catalog-only data in hypoDD. 21(C) Relocated hypocenters using both catalog and cross-correlated data in hypoDD. When using cross-correlated data in tandem with catalog data, relocated hypocenters tighten up significantly, narrowing down the areas and depths of seismicity on the island. The black ovals denotes the faint N-NW elongation seismicity on the maps.

Years are represented by the color scale, where purple to blue circles represent the early part of the subset (2003-2004), light blue to green circles are the middle years (2005-2006), and yellow to orange circles are the last year (2007); red circles would represent the start of 2008, but 2008 events are not included in this timeframe here.
Figure 22. Map and east-west cross section of seismicity located on and around Gareloi Volcano from 2003-2007, labeled by signal type (LP vs. HF). Dark purple circles represent LP seismicity, while cyan blue circles represent HF seismicity. White outline marks approximate boundary of Gareloi Island. White diamonds represent locations of Gareloi seismometers.

22A) Initial hypocenters, as located by AVO. 22B) Relocated hypocenters using catalog-only data in hypoDD. 22C) Relocated hypocenters using both catalog and cross-correlated data in hypoDD. The lavender ovals denote the faint N-NW elongation and cross-sectional area of LP seismicity, likely instigated by fluid movement and gas exsolution in the magma chamber. Cyan ovals demarcate the general area on the island and two cross-sectional areas HF seismicity occurs, possibly areas of dikeing. Hypocenter relocation with catalog-only data greatly tightens the areas of seismicity for both LP and HF events. When cross-correlated data and catalog data are used simultaneously, both areas of LP and HF seismicity tighten significantly, narrowing the areas and depths earthquakes on Gareloi occur.
Figure 23. Map and east-west cross section of 2007 multiplet seismicity during April-July. White outline marks approximate boundary of Gareloi Island. White diamonds represent locations of Gareloi seismometers. 23A) Initial hypocenters, as located by AVO. 23B) Relocated hypocenters using catalog and cross-correlated data in hypoDD, color-coded by month activity (where dark red circles are the April/May events, magenta pink circles are June events, and coral pink circles are the July events). 23C) Relocated hypocenters color-coded by signal type (where dark purple circles represent LP seismicity, while cyan blue circles represent HF seismicity) display the entirety of the 2007 multiplets are LP seismicity, possibly the result of gas exsolution after injection of new magma into the system. Relocated hypocenters display a significant tightening and narrowing of seismicity beneath the island. The wide range of relocated hypocentral depths after waveform cross-correlation indicate our depths are not well-constrained.
Figure 24. Map and east-west cross section of seismicity located on and around Garlovo Volcano from 2008-2015, the time period when Garlovo seismometers experienced frequent outages and poor station health. White outlines mark approximate boundaries of Garlovo, Kavalga, Ogluca, and Skagull Islands. White diamonds represent locations of Garlovo seismometers. 24A) Initial hypocenters, as located by AVO. 24B) Relocated hypocenters using catalog-only data in hypoDD. 24C) Relocated hypocenters using both catalog and cross-correlated data in hypoDD. Due to the frequent station outages and poor network health, the vast majority of seismicity was recorded during this time frame displayed HF behavior. Only around 400 events were locatable by AVO analysts. Also, during this period, in 2012, AVO switched location programs from Hypoellipse to Hypoinverse; AVO scientists did not see a drastic change in relocations when comparing the results of the two programs (Powers et al., 2019).

Years are represented by the color scale, where purple to blue circles represent the early part of the subset (2008-2010), light blue to green circles are the middle years (2011-2013), and yellow to orange circles are the last years (2014-2015); red circles would represent the start of 2016, but 2016 events are not included in this timeframe here.
Figure 25. Map and east-west cross section of seismicity located on and around Gareloi Volcano from 2016-2019, using GMT. White outlines mark approximate boundaries of Gareloi, Kavalga, Oglia, and Skagul Islands. White diamonds represent locations of Gareloi seismometers. 25A) Initial hypocenters, as located by AVO. 25B) Relocated hypocenters using catalog-only data in hypoDD and show a significant amount of scattered locations and depths compared to 2003-2007. 25C) Relocated hypocenters using both catalog and cross-correlated data in hypoDD. When using cross-correlated data in tandem with catalog data, relocated hypocenters tighten up even more.

The black ovals denotes the approximate the W-NE trend seismicity on the maps and range of area and depth in cross sections. The light blue ovals in the map view and cross section of 25B demarcate an area of significant regional (HF) seismicity between Gareloi and Tanga Islands during May 2017. The red ovals in the map view and cross section of 25B approximate an area of Gareloi-centric HF seismicity which took place November 2017.

Years are represented by the color scale, where purple to blue circles represent the early part of the subset (2016-2017), green circles are 2018, and yellow to orange circles are the last year (2019); red circles would represent the start of 2020, but 2020 events are not included in this timeframe here.
Figure 26. Map and east-west cross section of total seismicity located on and around Gareloi Volcano from 2016-2019, labeled by signal type (LP vs. HF). Dark purple circles represent LP seismicity, while cyan blue circles represent HF seismicity. White outlines mark approximate boundaries of Gareloi, Kavalga, Ogluga, and Skagul Islands. White diamonds represent locations of Gareloi seismometers. 26A) Initial hypocenters, as located by AVO. 26B) Relocated hypocenters using catalog-only data in hypoDD and show a significant tightening of location on the map in the W-NE trend on the map and cross section, though relocation still remain fairly scattered. 26C) Relocated hypocenters using both catalog and cross-correlated data in hypoDD. When using cross-correlated data in tandem with catalog data, relocated hypocenters tighten up even more. All seismicity, located LP and HF, demonstrate the overall W-NE trend and no clear areas of one-seismic signal only in cross section to be demarcated by ovals, as in previous figures.

The light blue ovals in the map view and cross section of 26B demarcate an area of significant regional (HF) seismicity between Gareloi and Tanga Islands during May 2017. The red ovals in the map and cross section views in 26B and 26C approximate an area of the Gareloi-centric HF seismicity; many of these events took place November 2017.
Figure 27. Rough sketch of Mount Garloei and its proposed interior as a highly fractured, homogenous structure, represented by the sharp black scatters throughout the edifice. This allows for fluid movement through the edifice, instigating the vast LP seismicity throughout the island. The large gray oval with black stars is an approximated representation of the large area beneath Garloei where the vast majority of seismicity throughout the study occurred; the black stars represent earthquake hypocenters. The seismicity of this study spans from 0 km (sea level) to approximately 20 km, which allows us to infer about the volcano’s structure to this depth. However, the vast majority of seismicity occurs between 1 km to 15 km depth. Additionally, we cannot speculate about the structure or seismicity of Garloei beneath 20 km, it was not examined for this study.

The scales above sea level and below sea level are not equal.
Figure 28. Histogram for all Gareloi data from 2003-2019 based on event magnitudes recorded on the seismic network. The vast majority of Gareloi earthquakes record with magnitudes under M1.5 which is typical for LP seismicity. No events above past 4.4 were found, and all of these events were likely the dissipated energy from larger regional events in the area.
Appendix A

MATLAB Scripts

1: Cross Correlation via Gismo (Thompson & Reyes, 2018)

For Cross Correlation

%startup_GISMO
q = dir('*GAEA*.2007*');
scnl = scnobject('GAEA', 'EHZ', 'AV');
k=1;
for j = 1:length(q); % loop over however many files are in the list
    f = q(j).name; % pull out the name of the ith file and call it "f"
    ds=datasource('sac', f);
    start=get_sacdate(f);
    endt=start+90/(24*3600);
    w(k)=waveform(ds, scnl, start, endt);
    k=k+1;
end
%plot(w)
t=get(w, 'start');
c=correlation(w, t);
plot(c)
cr=xcorr(c);
plot(cr, 'corr')
%c1=subset(c, [1:100:length(q)])
plot(cr)
cr=xcorr((c), [5 45]);
corr=get(cr, 'corr');
lag=get(cr, 'lag');

cr=linkage(cr);

plot(cr, 'den');
in=find(c,'clust', 1:5);
c1=subset(c, in);
c1=sort(c1);

plot(adjusttrig (c1))
plot(c1, 'corr')
axis square
axis tight

%plot(sort(c1), 'corr')

To Make a Waveform Object

q = dir('*GAEA*2007*'); % choose all GAEA data from 2007
chantag = 'AV.GAEA..EHZ';
for i = 1:length(q);
    f = getfield(q(i), 'name');
    [x,h]= readsac(f, 'l');
    d = get_sacdate(f);
    Fs = 1/h.DELTA;
    w(i) = waveform(chantag, Fs, d, x);
end
t = get(w, 'start');
c = correlation(w,t);

*For Gareloi 2007 Multiplets*

load c_GAR

w = waveform(c);
c=cluster(c, 0.7);
in=find(c, 'clust', 1:5);
c0=subset(c, in);
c0=sort(c0);
c0 = crop(c0, [20 70])
plot(adjusttrig (c0))
plot(c0, 'corr')
axis square
axis tight

%Create indices 1-5 from c's above parameters
%Create associated waveform objects
%Create EVID for each indice cluster (can only use r,w,a,+,b,A,W,t for
%fopen, so name waveforms based on those letters)

%Indice 1
in1=find(c,'clust', 1,3);
c1=subset(c, in1);
c1=sort(c1);
plot(adjusttrig (c1))
plot(c1, 'corr')
axis square
axis tight
%use W
w1 = waveform(c1);
EVID1 = get(w1, 'EVID');
 fid1 = fopen('AprilMay.list', 'w'); % create file, and give it a file indicator (fid)
for i = 1:length(EVID1) % loop over all events
    fprintf(fid1, '%d %d
', EVID1(i), EVID1(i)); % print formatted data to file
end
fclose(fid1) % close the file

%Indice 2
in2=find(c,'clust', 2,5);
c2=subset(c, in2);
c2=sort(c2);
plot(adjusttrig (c2))
plot(c2, 'corr')
axis square
axis tight
%use a
w2 = waveform(c2);
EVID2 = get(w2, 'EVID');
 fid2 = fopen('July.list', 'w'); % create file, and give it a file indicator (fid)
for i = 1:length(EVID2) % loop over all events
    fprintf(fid2, '%d %d
', EVID2(i), EVID2(i)); % print formatted data to file
end
fclose(fid2) % close the file

%Indice 4
in4=find(c,'clust', 4);
c4=subset(c, in4);
c4=sort(c4);
plot(adjusttrig (c4))
plot(c4, 'corr')
axis square
axis tight
%use A
w4 = waveform(c4);
EVID4 = get(w4, 'EVID');

fid4 = fopen('June.list', 'w'); % create file, and give it a file indicator (fid)
for i = 1:length(EVID4) % loop over all events
    fprintf(fid4, '%d %d
', EVID4(i), EVID4(i)); % print formatted data to file
end
fclose(fid4) % close the file

Cross Correlation Endnotes:

1. c_GAR will load the correlation object “c_GAR.mat”, created by Dr. Jackie Caplan-Auerbach and Jim Long which contains the phase file event identification numbers (EVIDs) for all Gareloi earthquakes. These EVIDs were then used to help identify and separate the distinct phases of the April-July 2007 multiplet activity, which in turn were able to be plotted in GMT.

   Further, EVIDs were matched to up to their corresponding earthquake signal type. I then created specific signal EVID lists and used to plot the locations and relocations of our specific earthquake signals in GMT.

   Please contact for further details and scripts regarding the identification and separation of event signals types based on EVIDs.
2. Originally, each of the distinct phases were separated out by the cluster number assigned by MATLAB, based on how similar the events were, instead of by time. Clusters 1 and 3 occurred in the April-May sequence, Cluster 4 was June, and Clusters 2 and 5 were the July events. Once I sorted by time, I referred to multiplet sequences by the months, hence, why there is no EVID3 or EVID5 for the second set of multiplet events during the April-May and July sequences, respectively, as they have been included into EVID1 and EVID2.
Appendix B

**ph2dt, hypoDD, & Cross Correlation Scripts**

1: *ph2dt.inp Example*

* ph2dt.inp - input control file for program ph2dt

* Input station file:

stations.dat\(^1\)

* Input phase file:

Gareloi.pha\(^2\)

*MAXDIST*: max. distance in km between event pair and stations [225]

*MAXSEP*: max. hypocentral separation in km [5]

*MAXNGH*: max. number of neighbors per event [12]

*MINLNK*: min. number of links required to define a neighbor [6]

*MINOBS*: min. number of links per pair saved [4]

*MAXOBS*: max. number of links per pair saved [50]\(^3\)

*MINWGHT* \(^4\) MAXDIST MAXSEP \(^5\) MAXNGH \(^6\) MINLNK \(^7\) MINOBS \(^8\) MAXOBS \(^9\)

| 1 | 225 | 5 | 12 | 6 | 4 | 50 |

*ph2dt.inp Endnotes:*

1. For station health tests, the “stations.dat” file was replaced with .dat which excluded a particular Gareloi network station I was tested; for example, when testing the effect of removing station GAEA from our data, the .dat file used was “stationsNOgaea.dat”.

2. The input phase files changed depending on which subset were tested. The file “Gareloi.pha” contains the phase files for all Gareloi earthquakes. When relocating
earthquakes from the three specific subsets, I used files “2003to2007”, “2008to2015”, and “2016to2019”, in place of “Gareloi.pha”, as these files only contained the phase files from those specific subsets.

3. The numbers within the brackets did not need to match those listed below for ph2dt to run and mainly functioned to keep the parameter tests organized. Only the numbers in the final line were needed for ph2dt to run successfully.

4. A MINWGHT of 0 was used initially in early trials and was later increased to 1 to constrain results using only the most reliable picks.

5. A MAXSEP of 5 was the most commonly used parameter throughout our trials, but I also used MAXSEPS of 8 and 3 to either broaden or constrain our trial results as well.

6. MAXNGH stayed fairly consistent at around 12 for the majority of trials, but depending on which subset I were preparing to relocate, this parameter either increased or decreased, based on the total numbers within the subsets.

7. When running the full Gareloi dataset, the 2003-2007 subset, and the 2016-2019 subset through ph2dt, a MINLNK of 6 was consistently used throughout the vast majority of trials, due to the large number of events within those files. However, as there were only ~400 events for the 2008-2015 subset, a MINLNK between 1-3 was typically used.

8. When running the full Gareloi dataset, the 2003-2007 subset, and the 2016-2019 subset through ph2dt, a MINOBS between 3-5 was consistently used throughout the vast majority of trials, due to the large number of events within those files. However, as there were only ~400 events for the 2008-2015 subset, a MINOBS of 1 was used.

9. For early trials of 2003-2007, a MAXOBS of 100 was initially used, but this was later decreased to 50 to better constrain our results and to remain consistent with the trials performed on the full data set and other two subsets.

2: hypoDD.inp Example

* RELOC.INP:

*--- input file selection

* cross correlation diff times:

dt0319.cc

* 

*catalog P diff times:
dt.ct³

* event file:
event.dat
*

* station file:
stations.dat
*

*--- output file selection
* original locations:
0319ctcc_16.loc⁵
* relocations:
0319ctcc_16.reloc⁵
* station information:
hypoDD.sta
* residual information:
hypoDD.res
* source parameter information:
hypoDD.src
*
*--- data type selection:
* IDAT: 0 = synthetics; 1= cross corr; 2= catalog; 3= cross & cat
* IPHA: 1= P; 2= S; 3= P&S
* DIST:max dist [km] between cluster centroid and station
* IDAT IPHA DIST
*--- event clustering:
* OBSCC: min # of obs/pair for crosstime data (0= no clustering)
* OBSCT: min # of obs/pair for network data (0= no clustering)
* OBSCC: 6  OBSCT: 7

*--- solution control:
* ISTART: 1 = from single source; 2 = from network sources
* ISOLV: 1 = SVD, 2 = lsqr
* NSET: number of sets of iteration with specifications following
* ISTART ISOLV NSET
  2  2  4

*--- data weighting and re-weighting:
* NITER: last iteration to used the following weights
* WTCCP, WTCCS: weight cross P, S
* WTCTP, WTCTS: weight catalog P, S
* WRCC, WRCT: residual threshold in sec for cross, catalog data
* WDCC, WDCT: max dist [km] between cross, catalog linked pairs
* DAMP: damping (for lsqr only)

* --- CROSS DATA ----- ---- CATALOG DATA ----
* NITER WTCCP WTCCS WRCC WDCC WTCTP WTCTS WRCT WDCT DAMP
  10  0.1  0.0 -9  2  1  0.1  5  2  610
10  1  0.0  -9  5  0.1  0.0  5  5  470
10  0.8  0.0  -9  3  0.7  0.5  5  3  390
10  0.5  0.0  -9  3  0.5  0.2  5  3  370

*--- 1D model:

* NLAY: number of model layers
* RATIO: vp/vs ratio
* TOP: depths of top of layer (km)
* VEL: layer velocities (km/s)

* NLAY  RATIO
     8  1.73
* TOP
0.0  1.8  3.0  7.0  13.0  18.0  23.0  36.0
*VEL
4.0  4.5  5.0  5.6  6.9  7.2  7.8  8.1
*

*--- event selection:

* CID: cluster to be relocated (0 = all)
* ID: cuspids of event to be relocated (8 per line)

* CID
0
* ID

**hypDD.inp** Endnotes:

1. Please contact for further parameter examples.
2. Files ending with .cc indicate files of cross correlated waveforms for hypoDD to incorporate into the relocations. The file “dt0319.cc” was used in the trials for the full
Gareloi dataset and the 2003-2007, 2008-2015, 2016-2019 subsets. For relocating 2007 multiplets, a file called “dt2007.cc” replaced “dt0319.cc”, as it only contained only 2007 earthquakes. However, as 2007 was the only year with events that could be cross correlated, hypoDD trials using .cc files primarily relocated 2007 events.

3. The file “dt.ct” contains the catalog data of events after undergoing ph2dt, and these are the events which hypoDD relocates.

4. For station health tests, the “stations.dat” file was replaced with .dat which excluded a particular Gareloi network station I were tested; for example, when testing the effect of removing station GAEA from our data, the .dat file used was “stationsNOgaea.dat”.

5. Initial location (.loc) and relocation (.reloc) files were named according to which dataset was being relocated with additional information. For catalog only trials (map/cross section Figures B), this additional information included OBSCT number and the trial number; for example, 03075_20 was trial 20 of subset 2003-2007 using an OBSCT of 5. For trials utilizing both catalog and cross correlated (map/cross section Figures C) included “ctcc” in place of OBSCT and trial number; for example 0319ctcc_16 was a trial 16 on the full Gareloi dataset using both catalog (ct) and cross correlated (cc) data. The OBSCT and OBSCC parameter numbers in the “ctcc” trials are included in project notes; please contact for further information about these trial parameters.

6. The parameter OBSCC functions similar to OBSCT, but considers cross correlated files rather than catalog.

7. I primarily used an OBSCT of 5 in our trials, but relocating the full Gareloi dataset with both catalog and cross correlated data required using an OBSCT of 6.

8. Please refer to Waldhauser (2001) for further details on hypoDD parameter functions.

3: Cross Correlation via Dr. Zhigang Peng’s Waveform Cross Correlation Package

http://geophysics.eas.gatech.edu/people/cwu/teaching/hypoDD/hypoDD.html

Direction for Cross Correlation (provided by Dr. Jackie Caplan-Auerbach)

To cross-correlate Gareloi data and output a dt.cc file, we use the following:

1. SAC_add_pick_crscrl.m
2. crscrl_GAREOI.sh
3. crscrl_event_pair_p.pl
4. sac_wfcc_no_swap
Data are first pre-processed in MATLAB using SAC_add_pick_crsrcl.m. The purpose of this step is to include the P-wave arrival time in the SAC header. P wave arrival times are taken from the phase file Gareloi.pha. Because sac_wfcc takes the earthquake origin time to be t = 0, the P-wave time is measured relative to the earthquake origin time, not the file start time. This is shown in the figure below where the red dot represents the earthquake origin time and the green dot represents the P arrival. In the SAC header, the file start time (hdr.BEG) is defined relative to the earthquake origin time, so in the example below hdr.BEG = -26.92 s. The P wave arrival is calculated relative to the earthquake origin (here this is 2.31 s), and is put into both the ARR and T0 positions. Header value h.ORG is defined as zero—this establishes the zero time from which other values are measured. Since the origin time is zero, the P wave arrival is also the travel time.

A file called “evid_tempid.list” is also required to run these programs. This is simply a text file listing all of the earthquake ID numbers and the folder name in which the data for that quake reside. In the case of GARELOI data, the name of each event directory is the ID number, so this file is simply the same value listed in two columns.

To perform the cross correlation we run the script crscrl_GARELOI.sh. This shell script calls the Perl script crscrl_event_pair_p.pl, which in turn calls the C code sac_wfcc. There are several versions of sac_wfcc, depending on whether the SAC data are little- or big-endian; for this purpose we are using sac_wfcc_no_swap, which means the data should not be byte-swapped (in other words, the data and platform use the same byte format).

crsrcl_GARELOI.sh gets all each event number from the evid_tempid.list file and loops over all other files. For each pair, it calls crscrl_event_pair.pl, which takes the two events, finds their P wave arrivals, brackets a time window around them, and calls sac_wfcc to do the actual cross-correlation and output a correlation coefficient. The time window around the P waves is established in crscrl_event_pair_p.pl as variable pwndw, as follows: $pwndw="-0.5/1.5/1.0"$. In this syntax, the first value is the time before the P arrival, the second is the time after the P, and the third value is the maximum time shift (it will not move things more than a second, in the example above). In crscrl_event_pair_p.pl you can also define which stations you want to cross
correlate, using the line open(WF1, "ls $event1/AV*GA*HZ*.SAC") or die "Can't open the pipe, $!
". In this version I've told it to only use waveforms with titles that have *GA*HZ* in them, which is to say Gareloi stations on the vertical channel. Finally, the script calls the actual cross-correlation function for each pair of events and outputs (a) the travel time difference between the two events, and (b) the correlation coefficient.

The file all_events_evid.list contains all Gareloi events—if you want to run the cross-correlation on all events, you’ll need to rename it “evid_tempid.list”. The current version of evid_tempid.list has a subset of events from 2007 that are well correlated.

Copy these scripts into a directory that sits just above the data directories. In other words, the folder in which you are working should have subfolders with names that are event IDs. You will also need to add /usr/local/sac/bin to your path as follows:

```bash
>>PATH=$PATH:/usr/local/sac/bin
```

To run crscrl_Gareloi.sh, use this syntax:

```
>> ./crscrl_Gareloi.sh
```

The output will be the dt.cc file you can use as input to hypoDD.

**Perl Script**

```perl
#!/usr/bin/perl

# do cross-correlation between pairs of events
# for all the possible stations
# output the median of the cc value
# doing P only, using z comp
# generate output for the purpose of hypoDD

# syntax: crscrl_event_pair_p.pl event1 event2
# usually pipe into | paste - -

if ($#ARGV<1) {
    die "syntax: crscrl_event_pair_p.pl event1 event2\n";
```
}  

# phase, P(a) or S(t0)
$pphase = "a";  

# for P
$pwndw="-0.5/1.5/1.0";  

# specify the progam
$sacst = "/usr/local/sac/bin/sacst";  # location of saclst binary
#$program = "/home/WWU/lallyk/bin/sac_wfcc/sac_wfcc_le";  #use little-endian version
$program = "/home/WWU/caplanj/sac_wfcc/sac_wfcc_no_swap";  #use unknown test version
$event1 = shift(ARGV);  
$event2 = shift(ARGV);  

# find out all the possible waveforms for event1 and event2  
# apply to the EHZ.SAC.bp file only
# bp between 2 to 16 Hz
# this line defines the events we're going to use--in this case
# only stations that have GA in them (Gareloi stations) on the
# vertical channel.
open(WF1, "ls $event1/AV*GA*HZ*.SAC") or die "Can't open the pipe, $!
";  
# this line is for waveform directories that have *.sac files
#open(WF1, "ls $event1/*HZ.sac") or die "Can't open the pipe, $!
";  
@wfs1 = <WF1>;  

close(WF1);  
open(WF2, "ls $event2/AV*GA*HZ*.SAC") or die "Can't open the pipe, $!
";  
#open(WF2, "ls $event2/*HZ.sac") or die "Can't open the pipe, $!
";  
@wfs2 = <WF2>;
close(WF2);

foreach $wf1 (@wfs1) {
    chomp($wf1);
    #print "# wf1=", $wf1, "\n";
    ($junk1,$stn1) = split(/\/, $wf1);

    # stn1 is AV.xxxx.yyyyyy, all we want is the first 7 characters
    # for .SAC files, strip all text up to and including the first period '.'
    # $stn1 =~ s/^[^.]*\.//;
    $stn1 = substr $stn1, 0, 7;
    #print "# after split, stn1=", $stn1, "\n";
    foreach $wf2 (@wfs2) {
        chomp($wf2);

        ($junk2,$stn2) = split(/\/, $wf2);

        # for .SAC files, strip all text up to and including the first period '.'
        # $stn2 =~ s/^[^.]*\.//;
        $stn2 = substr $stn2, 0, 7;
        #print "# after split, stn2=", $stn2, "\n";

        if ($stn1 eq $stn2) {
            print "# matched station ", $stn1, " and ", $stn2, "\n";

            # find the matched station pairs, calculate the cc between them
            print "# running saclst on ", $wf1, "\n";
            $output1 = `saclst $pphase f $wf1 | grep -v 12345.0000`;

            print "# running saclst on ", $wf2, "\n";
            $output2 = `saclst $pphase f $wf2 | grep -v 12345.0000`;

            if ( $output1 != "" & $output2 !="" ) {

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Shell Script

#!/bin/sh

# calculate the relative travel time using waveform cross-correlation
# output is dt.cc, used by the hypoDD program to determine the relative locations
# output file is dt.cc
rm -f dt.cc
rm -f crscrl_event_pair.out

# usage: ./crscrl_GARELOI.sh

# time difference DT = T1 - T2

# written by zpeng, Tue Mar 25 14:43:17 EDT 2008
# edited by jca, October 2020

# this code requires a table to match the CUSP id with data directory (for Gareloi, these are the same thing):

evid="evid_tempid.list"

#for eve1 in `gawk '{print $2}' $evid`
while read pha_id eve1; do

#echo "# Outer loop: PHA is $pha_id"
[ "$eve1" ] || echo "# eve1 is blank"

#dir1=`gawk '{print $2}' $evid`
#echo "outer loop, pha_id is $pha_id, eve1 is $eve1"
for eve2 in `gawk '{print $2}' $evid`

do

#echo " inner loop, eve2 is $eve2"
#
if [ $eve1 -lt $eve2 ]; then
  if [[ "$eve1" < "$eve2" ]]; then

    eve_sv1=`gawk '{if ($2 == "$eve1") print $1}' $evid`
    eve_sv2=`gawk '{if ($2 == "$eve2") print $1}' $evid`

# Output event pair data to dt.cc:
    echo "# eve1=$eve1  eve2=$eve2"
    # after the 8-digit event ID, plus 3 more characters of "AV." THEN the
    # station ID, in the second field in the input line. (like 60149878.AV.AXYZ.EHZ.sac)
    # echo "crscrl_event_pair_p.pl $eve1 $eve2"
    ./crscrl_event_pair_p.pl $eve1 $eve2 | tee -a crscrl_event_pair.out | sed 's/\// /g' | gawk '{if ($8>=0.0 && $8!= "nan") printf "AV%s %7.4f %6.4f P\n",substr($2,4,4), $3-$7, $8}' >> dt.cc

```

# for eve1 in `gawk '{print $2}' $evid`
while read pha_id eve1; do
  #echo "# Outer loop: PHA is $pha_id"
  [ "$eve1" ] || echo "# eve1 is blank"

  #dir1=`gawk '{print $2}' $evid`
  #echo "outer loop, pha_id is $pha_id, eve1 is $eve1"
  for eve2 in `gawk '{print $2}' $evid`
    do
      #echo " inner loop, eve2 is $eve2"

      #if [ $eve1 -lt $eve2 ]; then
      if [[ "$eve1" < "$eve2" ]]; then

        eve_sv1=`gawk '{if ($2 == "$eve1") print $1}' $evid`
        eve_sv2=`gawk '{if ($2 == "$eve2") print $1}' $evid`

        # Output event pair data to dt.cc:
        echo "# eve1=$eve1  eve2=$eve2"
        # after the 8-digit event ID, plus 3 more characters of "AV." THEN the
        # station ID, in the second field in the input line. (like 60149878.AV.AXYZ.EHZ.sac)
        # echo "crscrl_event_pair_p.pl $eve1 $eve2"
        ./crscrl_event_pair_p.pl $eve1 $eve2 | tee -a crscrl_event_pair.out | sed 's/\// /g' | gawk '{if ($8>=0.0 && $8!= "nan") printf "AV%s %7.4f %6.4f P\n",substr($2,4,4), $3-$7, $8}' >> dt.cc
```
#!/usr/bin/perl

#!/crscrl_event_pair_p.pl $dir1 $dir2 | sed 's/\// /g' | gawk '{if ($8>=0.5 && $8!=
"nan") printf "%s %7.4f %6.4f P\n",substr($2,4,4),$3-$7,$8*$8} >> dt.cc

#!/crscrl_event_pair_s.pl $eve1 $eve2 | sed 's/\// /g' | gawk '{if ($8>=0.5 && $8!=
"nan") printf "%s %7.4f %6.4f S\n",substr($2,4,4),$3-$7,$8*$8} >> dt.cc

fi

done

done < $evid
Appendix C

**GMT Scripts**

1: *Separating Seismic Signals (LP vs. HF) for Mapping*¹

```
#!/bin/bash

#LP locations (Change last extension based on which subset of data you are using!)
awk 'NR==FNR{ for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' LPevid.lst
/home/WWU/harri243/GARELOI/Test1/1619ctcc.loc > LP.loc

awk 'NR==FNR{ for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' LPevid.lst
/home/WWU/harri243/GARELOI/Test1/1619ctcc.reloc > LP.reloc

#HF locations (Change last extension based on which subset of data you are using!)
awk 'NR==FNR{ for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' HFevid.lst
/home/WWU/harri243/GARELOI/Test1/1619ctcc.loc > HF.loc

awk 'NR==FNR{ for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' HFevid.lst
/home/WWU/harri243/GARELOI/Test1/1619ctcc.reloc > HF.reloc
```

*Separating Seismic Signals (LP vs. HF) for Mapping* Endnotes

1. In order to create these signal separated files, the script prints identical first lines in new .loc and .reloc files based on the “master” file. To correct this, I cross referenced our first lines with our signal spreadsheets to confirm which signal list the first printed lines actually belonged to.

2: *2007 Multiplets Cluster Separation*¹

```
#For separating events by time²

#April/May locations (Change last extension based on which subset of data you are using!)
```
awk 'NR==FNR{for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' AprilMay.list /home/WWU/harri243/GARELOI/Test1/2007ctcc.loc > AprilMay.loc

awk 'NR==FNR{for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' AprilMay.list /home/WWU/harri243/GARELOI/Test1/2007ctcc.reloc > AprilMay.reloc

#June locations (Change last extension based on which subset of data you are using!)
awk 'NR==FNR{for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' June.list /home/WWU/harri243/GARELOI/Test1/2007ctcc.loc > June.loc

awk 'NR==FNR{for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' June.list /home/WWU/harri243/GARELOI/Test1/2007ctcc.reloc > June.reloc

#July locations (Change last extension based on which subset of data you are using!)
awk 'NR==FNR{for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' July.list /home/WWU/harri243/GARELOI/Test1/2007ctcc.loc > July.loc

awk 'NR==FNR{for (i=1; i<=NF;i++) a[$i];next} FNR==1 || ($1 in a)' July.list /home/WWU/harri243/GARELOI/Test1/2007ctcc.reloc > July.reloc

2007 Multiplets Cluster Separation Endnotes:

1. The cluster separation functions in the same manner as the signal separation detailed in the above Separating Seismic Signals (LP vs. HF) for Mapping. When using the cluster separation, I had to correct the first line of the new sequence .loc and .reloc files so they began with the appropriate months (i.e. removing an earthquake from April from the start of the June and July sequence files).

2. These steps are for mapping the 2007 multiplets by the three observed sequences (April-May activity in claret, June activity in cerise, and July activity in coral). After color-coding based on these sequences, I followed the steps in Separating Seismic Signals (LP vs. HF) for Mapping Examples to then map multiplet activity by seismic signal.