Accessible Volcano Monitoring Results for Nearby Communities: Tenerife, Canary Islands

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ABSTRACT

We live on a planet embroidered with 1,000 active volcanoes. Although some of these volcanoes are in remote places, volcanoes like those in the Canary Islands are contiguous to communities and visitors. In these circumstances, volcanic eruptions threaten human lives and cause severe financial consequences. Therefore, it is imperative that volcanoes are monitored to forecast prospective eruptions, and that neighboring communities understand the potency of volcanoes. This paper is an educational document that explains how volcanoes are observed and the risks of a volcanic eruption. It advocates for routine monitoring of volcanoes and the establishment of emergency action plans in at-risk communities. These two actions protect the lives of individuals and existing infrastructure, which reduces the financial burden associated with post-eruption recovery. Ultimately, if communities are made aware of their neighboring volcanoes’ behaviors and hazards, they can accurately assess the risks posed by an eruption and make educated choices in preparation for, amidst, and following a volcanic emergency. Through volcano monitoring, preparation, and education, human-earth coexistence can ensue.

Keywords: Volcanic Observation, Teide Volcanic Complex, Emergency Preparedness, Eruption, Plan of Action, Canary Islands
INTRODUCTION

Each year, 50-70 volcanoes erupt out of the 1,000 active volcanoes in the world (Heiken, 2016). How can communities surrounding active volcanic structures safely coexist with their environments? How can cities become more resilient? What is an appropriate evacuation plan? Most importantly, how can the results of routine monitoring of volcanoes be best communicated to the public to help people better understand volcanic risks? This paper aims to answer these questions. It strives to make the science of volcanic observation readily understood, in order to create a more informed public, who will, in turn, support preemptive measures such as evacuation plans that ensure the safety of a community. The island of Tenerife in the Canary Islands will serve as a case study to show how this might be accomplished. First, this paper will briefly outline the geological background and eruptive history of Tenerife, where I conducted geochemical research for volcano monitoring. Next, it will summarize the three mechanisms of volcanic observation, specifically, geochemical, seismic, and deformation measurements. Finally, the paper will summarize the relationship between specific volcanic risks and the elements of an evacuation plan.

GEOLOGIC BACKGROUND

Geologic Background of the Canary Islands

The Canary Islands, shown in Figure 1, is an archipelago that is comprised of 7 major islands. The archipelago is located in the Atlantic Ocean about 100km off the coast of Morocco and is situated on the Jurassic ocean crust. The islands formed in a West-Southwest and East-Northeast direction, where the Northeast and Southwest corners of the archipelago are the oldest and youngest islands, respectively. The archipelago reflects
the dynamic life cycle of volcanic structures, which experience a sequence of growth through high volcanic activity or construction, and eventual destruction via mass wasting and erosion. An island will grow when volcanic activity occurs at a faster rate than mass wasting, while the destructive phase occurs until a volcano erodes to sea level. Currently, the oldest islands, Lanzarote (>20.2Ma) and Fuerteventura (20.2Ma), are in their destructive phases as evidenced by flatter topography and diminished volcanic activity, while intermediate aged islands, Gran Canaria (14.6Ma) and Tenerife (11.9Ma), are in a transitional phase from construction to destruction. Islands west of Tenerife such as La Gomera (9.4Ma), La Palma (1.7Ma), and el Hierro (1.1Ma) are in their constructive phases (Carracedo et al., 2016; Hoernle et al., 2009).

Geochemically, in the early growth cycles of the constructive phase, volcanic activity produces highly silica-undersaturated rocks such as nephelinites and basanites. On the contrary, silica saturated and basaltic melts such as alkali basalts and transitional tholeiites are produced at the height of volcanic activity. Towards the end of volcanic activity, nearing the destructive phase, rock composition tends to become mafic and alkali. Each of these geochemical phases of volcanism corresponds with different physical structures: silica-undersaturated rocks in the early phase, subaerial shield volcanoes in the alkali basalt/tholeiite phase, and the remains of large-scale lateral collapses in the alkali rock/destructive phase (Carracedo et al., 2016).

Four main theories involving decompression melting postulate the formation of the Canary Islands. Decompression melting could occur “(1) along a leaky transform fault or propagating fracture (i.e., most likely an extension of the South Atlas fault system), (2) beneath rising lithospheric blocks as a result of tectonic shortening, (3)
beneath a suture zone running along the Atlantic margin of northwestern Africa, or (4) of an upwelling mantle plume” (Hoernle et al., 2009, p. 142). Regardless of the origins of the Canary Islands, this paper supports the regular observation of the archipelago’s volcanic processes to ensure the safety of its population and visitors.
Figure 1: This map of the Canary Islands shows its major islands and its formation from Lanzarote to El Hierro (Canarias. 2017).
**Geology of Tenerife**

Tenerife’s importance supersedes that of the other islands with regards to volcanic hazard, as it is the largest island in the Canarian Archipelago (2034km\(^2\)), is home to 889,936 inhabitants, and is visited by 5,000,000 tourists each year (Hernández et al., 2017; Geology Turismo, 2017). Tenerife attracts hikers, beach-goers, mojo taste-testers, and waterpark-enthusiasts; its most significant attraction, the Teide Volcanic Complex, receives more than two and a half million tourists per year (Dóniz-Paéz et al., 2017). Still, the Teide Volcanic Complex’s destructive potential is overlooked.

Tenerife is composed of three volcanic rifts and a central volcanic complex where the island’s greatest wonders—the twin stratovolcanoes of Pico Viejo and el Teide—reside. These elements are pictures in Figure 2. The United Nations Education, Scientific, and Cultural Organization (UNESCO) declared the Teide National Park a world heritage site to pay homage to its magnificence (Carracedo et al., 2013). At 3,717 meters in altitude, el Teide is the third highest volcanic structure in the world when measured from the ocean-floor. There is evidence supporting the island’s transition from its constructive to destructive phase. The Teide summit and las Cañadas formed through several stages of volcanism and both show evidence of basaltic to phonolitic cycles (Carracedo et al., 2013). Las Cañadas has since evolved from this construction through destructive collapses and landslides. Similarly, the Anaga Massif (North-East) and Teno Massif (North-West) symbolize the remains of shield volcanism where the basalts erupted from fissure vents. Although Tenerife’s volcanic activity seems to be declining, its geologic history suggests that an eruption may be overdue.
Figure 2. (a) View of Tenerife and the island’s significant geographical features (Google Maps, 2017). (b) El Teide and Pico Viejo are pictured on the map.
Historical Eruptive History of Tenerife

Teide is believed to have erupted in 1492, 1705, 1706, 1798, and 1909, and its prehistoric eruptive history is conjectured using geochemical dating. The concept of community-volcano coexistence is not novel; people have been coexisting with el Teide for centuries. In fact, before Spaniards occupied Tenerife, los Guanches inhabited the island and were aware of Teide’s power. Volcanology was once seen in a spiritual light. Many native people feared el Teide and saw it as Guayuota’s, god of the deceased, home or a gateway to hell. By the 18th century, superstition was replaced with science and volcanology divided into two theoretical frameworks: that of the Neptunists and of the Plutonists. The Neptunists debated that “all rocks, including what we now see as volcanic rocks, were marine deposits formed by chemical precipitation in the ocean” while the Plutonists argued, “volcanic rocks resulted from the solidification of molten masses from the Earth’s interior” (Carracedo et al., 2013, p.2). While the process of researching volcanoes had not yet begun, the debate between Plutonists and Neptunists gave validity to geology and volcanology as sciences.

The Guanches witnessed 6-8 eruptions, allowing them to look upon Teide with awe and respect, fear nonetheless, but a level of understanding of the gravity of Teide’s power. They adopted a symbiotic relationship with the volcano. They used the Cañadas for goat migration, the volcanic rocks for shelter, and mined the volcanic obsidian. Most recent eruptions are believed to have “had pre-eruptive stages characterized by felt earthquakes, gas emanations, thermal anomalies, underground noises, ground deformation, faulting, and changes in the volume and location of the natural water
courses” (Carracedo et al., 2007, p. 30). It is with this information that volcanic eruptions can be most accurately forecasted.

**Eruptive Timeline of Tenerife**

Understanding Tenerife’s eruptive history is important in determining present day hazard. Historical eruptions are classified as effusive, low in frequency, and moderate in intensity while the Holocene phonolitic eruptions can be defined by higher explosivity. Over time, Teide’s activity has declined but its recent behaviors indicate a reawakening. Historical eruptions are listed in Figure 3.
Figure 3. This timeline plots eruptions in Tenerife's recent history (Geology Turismo, 2017).
METHODOLOGY IN VOLCANIC OBSERVATION

The practices used to observe the Teide Volcanic Complex are consistent with those used by volcanic observatories around the world. Ultimately, (1) geochemistry, (2) seismicity, and (3) land deformation must be monitored in order to detect volcanic unrest and forecast pending volcanic eruptions. If drastic changes occur simultaneously in these three measures, an eruption may be imminent.

1. Geochemical Analysis

In between activity, volcanoes can emit gas in ways that are both visible and non-visible. Since carbon dioxide is a major gas species in volcanic fluids/magmas, it is an effective indicator of subsurface magma degassing. The trends of carbon dioxide efflux values and other chemical measures such as helium or radon are then helpful in delineating faults, and drastic efflux changes can be indicative of a subsequent eruption (Peréz et al., 2013; Padrón et al., 2013).

El Instituto Volcanológico de las Islas Canarias (IN VOLCAN) regularly monitors volcanic activity in Tenerife and other Canarian islands (Instituto..., 2017). Each survey selects sampling sites through use of a Global Positioning System (GPS) and measures for carbon dioxide efflux are taken at each site by means of a portable non-dispersive infrared (NDIR) carbon dioxide analyzer. The chamber is connected to corresponding data acquisition software. After calibration, the chamber is held perpendicularly to face open-air and then placed over the ground, allowing gas to enter the chamber and the analyzer. Concentration of carbon dioxide is measured as a function of time. Then, a sequential Gaussian simulation (sGs) generates a map that estimates carbon
dioxide discharge (Peréz et al., 2013). The field methods of geochemical volcano monitoring are pictured in Figure 4.

Additionally, soil gas samples are collected from depths of 30-50cm through a metallic soil probe and hypodermic syringe, and are injected into a pressurized vial. These vials are analyzed by means of micro-gas chromatograph, quadrupole mass spectrometer, and stable isotope ratio mass spectrometer for various geochemical components (Peréz et al., 2013). Principally, elevations in helium are indicative of volcanic awakening (Padrón et al., 2013). The laboratory methods of geochemical volcano monitoring are pictured in Figure 5.

In the North-East Rift Zone (NERZ), the most recent eruptions occurred from 1704 to 1705. In the summer of 2017, diffuse carbon dioxide values ranged from 0 to 41.1 gm⁻²d⁻¹, which translates to an emission rate of 1,361 ± 35 td⁻¹. This value was higher than the background average and previously observed values (Rodríguez et al., 2017). The North-West Rift Zone (NWRZ) is the most active region on Tenerife. Historically, it is home to the eruptions of Boca Cangrejo S. (XVI), Arenas Negras (1706), and Chinyero (1909). The soil Carbon dioxide efflux values of the 2017 survey ranged from undetectable to 46.6 gm⁻²d⁻¹ and the average carbon dioxide output was estimated to be 297 ± 13 td⁻¹, a value higher than previously recorded rates (García et al., 2017).

In February of 2017, diffuse degassing in the summit of El Teide increased from 20 tons/day to 175 tons/day. This significant increase in degassing has prompted weekly monitoring at the Teide summit in place of monthly monitoring (D’Auria et al., 2017a).
Figure 4 illustrates the standard routine when conducting volcano geochemical monitoring field work. First, the site is located using a Global Positioning System. Upon arriving, the accumulation chamber is placed on the ground and synchronized with the data acquisition software to collect CO2 efflux. Three hypodermic syringes are used to fill three pressurized vials with the gas that is directly under the accumulation chamber. Meanwhile, three soil gas samples are collected from depths of 30-50cm through a metallic soil probe and injected into pressurized vials. Soil temperatures are noted at depths of 20cm and 40cm.
Figure 5. a) The vials containing the collected gases are sorted according to collection method: accumulation chamber or metallic soil probe. They are then analyzed through means of b) quadrupole mass spectrometer, c) micro-gas chromatograph, and stable isotope ratio mass spectrometer (not pictured) for various geochemical components.
2. Seismic Monitoring

Seismicity and magmatic degassing go hand-in-hand and indicate a magmatic pulse. Figure 6 shows the seismic network (consisting of 15 seismic stations) that was implemented in November 2016. It processes seismic activity in real-time (D’Auria et al., 2017a). Before deployment of this network, the majority of seismicity was detected between Tenerife and Gran Canaria and in the two major seismogenic zones in the Northwest and Southwest of the Teide Volcanic Complex (Melían et al., 2012). Notable periods of unrest occurred from 2001 to 2003 and from 2004 to 2005 (Hernández et al., 2017). Then, on February 10 of 2016, a swarm of long-period earthquakes was recorded (D’Auria et al., 2017b). While seismic activity is indicative of volcanic re-awakening, it is unclear how prognostic it can be, as increased seismic activity can last just hours before an eruption or at times, up to a year.

3. Land Deformation

The third ingredient to volcanic observation is land deformation, which occurs with changes in rock pore pressure (Pérez et al., 2013). Land deformation is measured via a Global Positioning System (GPS) such as the one in Figure 6c.

**Forecasting Volcanic Eruptions at el Teide**

In the case of el Teide, over the past 10 months, the volcano has experienced elevated helium levels, an increase in carbon dioxide efflux, and an increase in seismicity but has yet to incur land deformation. Although the Teide Volcanic Complex is experiencing a re-awakening, it is difficult to say with certainty that there will be an eruption.
Figure 6: a) The map marks seismic stations, Global Positioning System (GPS) stations, geochemical stations, and observational stations. b) Installation of station TSJR. c) Example of a seismic station, while c) is a GPS station (Instituto Volcánologico de Canarias, Spain).
VOLCANOES AND HUMANS AROUND THE WORLD

Monitoring Internationally

Most volcanoes form at plate boundaries, at either subduction or rift zones, or above hotspots. While there are over 100 volcano observatories in the world, only 35% of historically active volcanoes are monitored. Figure 7 illustrates global volcanoes. Most volcanoes experience precursory activity similar to that of el Teide before an eruption. However, the duration of these symptoms, changes in geochemistry, seismicity, and land deformation, can vary from days to years. Although the average period of unrest is about 500 days, about one half of researched stratovolcanoes erupted after one month of unrest. Despite the fundamental uncertainty of a volcanic eruption, equipment, real-time data recovery, understanding of the volcano’s history, scientific interpretation, public communication, and data dissemination create conditions for the most accurate eruptive forecast. In the case of historically active volcanoes that seem to have entered a period of repose for over 100 years, Satellite based Earth Observation may be a more cost effective monitoring method (Loughlin et al., 2015).

A volcano may seem like an exotic topographical element but it is a perilous neighbor for one tenth of the world’s population. In fact, over 29 million people live within 10 kilometers and 800 million people live within 100 kilometers of an active volcano. There are 1,508 active volcanoes in the world, located in 86 countries. With a substantial portion of the world’s population affected by this hazard, effective monitoring, communication, and emergency preparedness are vital. It is estimated that since 1600 AD, volcanic hazards have taken 280,000 lives (Brown et al., 2017). In
addition to being a direct threat to life, volcanic activity can threaten economy and local well-being.
Figure 7. The red triangles that overlay this map represent the volcanoes around the world. Volcanoes form at plate boundaries or above hotspots.

*Face of the Earth*
CLASSIFYING VOLCANOES

Explosivity

A volcano’s explosivity and effusivity can be predictive of its potential eruptive damage. The Volcanic Explosivity Index (VEI), Figure 8, categorizes an eruption’s explosivity according to an eruption’s duration and eruptive material. Eruptions of a VEI of 2-3 are likely to produce fatal incidents and eruptions of a VEI of 3-4 typically contribute to the highest number of fatalities (Loughlin et al., 2015).
Figure 8. The Volcanic Explosivity Index (VEI) allocates values for the explosivity of a volcano according to ejected material. The scale is logarithmic after a value of 2 (USGS).
Type of Eruption

Additionally, the explosivity of an eruption is correlated to its type as is pictured in Figure 9. Eruptions can be effusive, strombolian, hydrovolcanic, vulcanian, plinian, or a dome collapse (Gobierno de Canarias, 2010). However, the most common eruption style in the Canary Islands is strombolian. Knowing this information allows for a more accurate understanding of volcanic hazards and subsequently, a more suitable emergency plan of action. Figure 10 charts the eruption styles in Tenerife’s history and each style’s associated eruptive products. A brief description of styles of eruption can be found below.

*Effusive:* The lava flow is smooth with low gas levels and density. This eruption style is typically associated with basaltic magmas.

*Strombolian:* Strombolian eruptions are low in explosivity and have low viscosity magma pulses that contain gas bubbles.

*Hydrovolcanic or Phreatomagmatic:* A hydrovolcanic eruption is characterized by a highly explosive eruption caused when magma and water interact.

*Vulcanian:* When lava or bedrock impedes rising magma and the pressure of gases or steam overcomes this bedrock, an explosive vulcanian eruption occurs.

*Plinian:* Plinian eruptions produce pyroclastic flows/ballistics/high density ash.

*Domes:* A dome collapse occurs when gas concentrates beneath the dome.
Types of Volcanic Eruptions

Tipos de erupciones volcánicas

- Hawaiian
  - Effusive
  - Lava Domes

- Vulcanian
  - Freate-magnética en mar
  - Phreatomagmatic

- Strombolian
  - Column of gases and cinders

- Plinian
  - Plinian

Figure 9. Types of volcanic eruptions, adapted from García Mora.
Figure 13. a) Strombolian eruptions have been the most common eruption on Tenerife, however, the pie chart portrays other styles of eruptions that have occurred in the past 250ka and b) presents eruption types on Tenerife as a flowchart. This figure was adapted from Marti et al., 2008.
VOLCANIC HAZARDS

The island of Tenerife is prone to the hazards of lava, ash, ballistic projectiles, and pyroclastic flows in a volcanic eruption (Gobierno de Canarias, 2010). Volcanic hazards threaten human life, animal life, industry, and infrastructure. This section will outline the products of a volcanic eruption and the direct and indirect hazards that these products pose. Each hazard will be defined and linked to a consequence (Brown et al., 2017). Illustrations of each volcanic hazard are featured in Figure 11.

*Volcanic Ash*: Volcanic ash is fragmented rock that when in large volumes can create conditions for hazardous driving and aviation, damage infrastructure, and hinder vegetation. Volcanic ash may be present from months to years following an eruption and may cause toxicological injury.

*Ballistics*: Ballistics are volcanic bombs that launch from the eruptive site. They pose danger to lives and infrastructure. When encountered, they may cause mechanical injury.

*Pyroclastic Density Currents*: Pyroclastic Density Currents (PDC) are responsible for $\frac{1}{3}$ of documented volcanic fatalities. In its wake, it is inescapable as a PDC may travel up to hundreds of km/hr and reach hundreds of degrees in Celsius. Therefore, a PDC may cause thermal injury. PDCs consist of flows, surges, and blasts.

*Flows*: Flows are avalanches of volcanic rocks, ash, and gases.

*Surges*: Surges are all consuming clouds of volcanic ash and gases.

*Blasts*: A blast is a PDC that reaches velocities of 100 m/sec or more.
**Lahars**: Lahars consist of volcanic debris and water that travel rapidly. They may cause mechanical injury.

**Debris Avalanches, Landslides, Tsunamis**: The collapse of material on the flanks of a volcano may cause an avalanche or landslide. If the collapsed material arrives at a body of water, depending on the scale of the collapse, a tsunami may arise.

**Volcanic Gases and Aerosols**: When a volcano erupts, it emits gases associated with magma production. In high concentrations, carbon dioxide, fluorine, and chlorine can lead to asphyxiation and be lethal. Gases and aerosols may cause toxicological injury.

**Lava**: A lava flow will cause thermal injury and destroy anything it encounters.

**Volcanic Earthquakes**: Although volcanic earthquakes typically have a magnitude of less than 5, they can damage infrastructure.

**Lightning**: Lightning can occur during an eruption, and might cause electrical injury.

**Secondary Hazards**: Secondary hazards are indirect consequences of a volcanic eruption and historically are to blame for 65,000 fatalities. These hazards include famine, water contamination, crop failure, and pollution. An ineffective evacuation is another risk. As imagined, a volcanic emergency can trigger psychological distress.
**Volcanic Fatalities**

Brown et al. conducted a study that aimed to update a volcanic fatalities database. The database contains information about 635 records of 278, 368 fatalities from 1500 to 2017. Each incident, or volcanic event, is documented with the number of fatalities, the fatal cause (volcanic hazard), and the distance of the affected individual from the volcanic event. As expected, individuals located closest to the site of the eruption were the predominant victims. In fact, about 50 percent of the documented fatalities occurred within 10km of the volcanic crater. The most affected populations included residents, scientists, tourists, media, and emergency responders. Ballistics were the most common cause of fatality for the incidents located closest to the eruptive site, while pyroclastic density currents were more likely to cause fatality as the distance increased. Brown et al.‘s study emphasizes that the chance of enduring a fatality is strongly dependent on distance from eruptive site. Therefore, one way to minimize volcanic fatalities is to reduce the number of individuals within 10km or 100km of a volcano (Brown et al., 2017). Figure 12 charts the percentage of volcanic fatalities that are attributed to each volcanic hazard.
Figure 12. Volcanic fatalities categorized by volcanic hazard. Adapted from Brown et al., 2017.
Hazard, Exposure, and Vulnerability

Hazard, exposure, and vulnerability consider historical eruptive trends, the locations of communities, and communities’ susceptible industries in the event of an eruption. The three categories are defined below.

*Hazard:* Hazard refers to the probability that a volcanic eruption will occur. A volcanic hazard event tree is a useful aid for determining this probability, as it is a visual representation of prior erupted products, eruption recurrence, and potential future impact.

*Hazard of Tenerife:* After analysis of geological data, Martí et al. created event trees similar to the one shown in Figure 13 by determining the probability that a vent would open for basaltic and phonolitic eruptions (Martí et al., 2008a).

*Exposure:* Exposure is measured according to physical proximity to volcanic hazards and the direct risk to life that these hazards pose. Figure 14 charts the population sizes that are exposed to volcanic hazards.

*Exposure on Tenerife:* Annually, 5,889,936 people are exposed to potential volcanic activity on Tenerife as it is home to 889,936 inhabitants and is visited by 5,000,000 tourists each year (Hernández et al., 2017; Geology Turismo, 2017). As population increases, hazard does as well.
Vulnerability: Vulnerability is the physical and social likelihood for damage. For example, accessibility of transportation in the case of evacuation is a measure of a community’s vulnerability. Figure 15 is a flowchart of the data sets that shed light on volcanic susceptibility.

Vulnerability of Tenerife:

The vulnerability of the Canary Islands is evaluated according to the measures of:

❖ Effect on Human Life
  ➢ This is determined through population density, the population of individuals that live with disability or illness, road networks and accessibility to mobility in the case of an emergency evacuation, the terrain and potential of unstable ground, and climatological factors that could compound a volcanic emergency.

❖ Environment
  ➢ There are environmental factors that are vulnerable in a volcanic eruption. Forty percent of Tenerife is protected ecosystem that would be threatened by a volcanic disaster. Additionally, forest density, aquifer contamination, and agricultural damage must all be considered.

❖ Effects on Infrastructure
  ➢ In a volcanic event, the infrastructure that enables the transport of goods such as power lines, roads, and airports has potential to be affected. Water and treatment plants fall into this category (Gobierno de Canarias, 2010).
Figure 13. Hazard map for the Teide-Pico Viejo Volcanic Complex. Adapted from Marti et al., 2008.
Figure 14. Pie chart shows the percentage of the world’s volcanoes that exist at different population sizes. Adapted from Loughlin et al., 2015.
Figure 15. Datasets utilized to assess volcanic susceptibility. Adapted from Marti et al., 2010.
Risk

Risk is a holistic analysis that unites hazard, exposure, and vulnerability. It can be represented by the equation:

\[
Risk = \frac{Hazard \times Exposure \times Vulnerability}{Coping Capacities}
\]

Tenerife has been divided into six zones as a means of differentiating the levels of risk on various parts of the island. However, it is important to note that eruptive risk is always present on the volcanic island of Tenerife (Gobierno de Canarias, 2010).

*Las Cañadas*: While las Cañadas is highly explosive; it is not populated and is likely to experience pre-eruptive signs that would allow for an accurate anticipation of a volcanic eruption. So, this region has low vulnerability with respect to people and infrastructure and presents low risk.

*Peak and North Side of Teide-Pico Viejo and Icod Valley*: The largest hazard in this area is a dome or lateral collapse alongside lava flows and high-speed clouds. The area is densely populated so it is highly vulnerable and at a high risk.

*Dorsal NE Summit and its North Flank*: This region could experience a hydromagmatic eruption, which is highly eruptive, due to its proximity to the coast. This area is highly vulnerable and at high risk should a hydromagmatic eruption occur.
Dorsal NW Summit and Southeast Flank: Since the Southeast flank has a decreased slope, its eruptive products would travel more slowly than from the other flanks. This risk is lower than that of the North Flank.

NE Dorsal and North Flank and South Flank: Contrary to the Dorsal NW Summit and the Southeast flank, the NE Dorsal and North Flank have increased slopes so erupted products would travel quickly. These areas present a high risk.

Anaga and Teno Massif: These regions on the island are in their destructive phases and therefore, present a low risk.

RISK REDUCTION

In order to reduce risk among a natural hazard, a community must first prioritize risk reduction. As for the Canary Islands, while El Instituto Volcanológico de Canarias (INVOLCAN) has routinely and meticulously monitored volcanic activity on the Canary Islands for 25 years, it was not until 2005 that the archipelago established an emergency plan of action. This step was pivotal in demonstrating support of emergency preparedness and ultimately, in reducing risk. Still, the information gap between scientists and the general public must be bridged. INVOLCAN hosts a variety of educational seminars that are scantily attended. Whether it be that locals do not feel endangered by a volcanic eruption and feel no need to attend, or simply are unaware of the occurrence of the educational event, there must be a more effective method for educating the public on volcanic risks prior to and during an eruption, and for articulating the logistics of an emergency action plan. The Hyogo Framework for Action 2005-2015: Building the
Resilience of Nations and Communities to Disasters of the United Nation set the precedent for risk reduction by creating the five priority actions listed in Table 1. The Canary Islands should strive to satisfy each step that the framework provides.
Priority Action 1: Ensure that disaster risk reduction is a national and a local priority with a strong institutional basis for implementation.

Countries that develop policy, legislative and institutional frameworks for disaster risk reduction and that are able to develop and track progress through specific and measurable indicators have greater capacity to manage risks and to achieve widespread consensus for, engagement in and compliance with disaster risk reduction measures across all sectors of society.

Priority Action 2: Identify, assess and monitor disaster risks and enhance early warning.

The starting point for reducing disaster risk and for promoting a culture of disaster resilience lies in the knowledge of the hazards and the physical, social, economic and environmental vulnerabilities to disasters that most societies face, and of the ways in which hazards and vulnerabilities are changing in the short and long term, followed by action taken on the basis of that knowledge.

Priority Action 3: Use knowledge, innovation and education to build a culture of safety and resilience at all levels.

Disasters can be substantially reduced if people are well informed and motivated towards a culture of disaster prevention and resilience, which in turn requires the collection, compilation and dissemination of relevant knowledge and information on hazards, vulnerabilities and capacities.

Priority Action 4: Reduce the underlying risk factors.

Disaster risks related to changing social, economic, environmental conditions and land use, and the impact of hazards associated with geological events, weather, water, climate variability and climate change, are addressed in sector development planning and programmes as well as in post-disaster situations.

Priority Action 5: Strengthen disaster preparedness for effective response at all levels.

At times of disaster, impacts and losses can be substantially reduced if authorities, individuals and communities in hazard-prone areas are well prepared and ready to act and are equipped with the knowledge and capacities for effective disaster management.

Table 1. Five actions that build a city resilient to disaster. From Hyogo Framework for Action (HFA), 2013.
This framework can be applied to any natural hazard but when applied to a volcanic setting, it means the following:

In order to identify areas at risk, there must be a thorough understanding of the stratigraphy, geochronology, petrology, and eruptive history of the volcano. Information about the volcano can be created and shared through hazard maps, probabilistic event trees, and global databases. To monitor the volcano, there must be access to technology and transparent communication. This information can be shared in conferences, which foster an exchange of ideas. There is a significant discrepancy in knowledge between developing and developed nations (Hyogo Framework for Action (HFA), 2015).

When further developing a city, volcanic hazard should be considered. Above all, the key ingredients to successful emergency preparedness are strong communication between scientists, local governments, emergency responders, and the general public. As mentioned before, capable scientists and technologies monitor the Canary Islands; this step is sufficiently satisfied. Additionally, the archipelago has a thorough emergency action plan in place. However, the communication of the science and related policy to the general public is feeble and demands more attention.

**Emergency Planning**

Perhaps, Canarians and tourists feel immune to volcanic disaster and for this reason neglect their surrounding volcanic structures. It should be noted that from 2004–2013, around two billion people in the world were directly affected by disaster. Thus, it is not only relevant but also imperative that communities (such as the Canary Islands) that are affected by hazards have an emergency plan that invokes pre-established procedures. An effective emergency plan is one that is borne out of the collaboration of various
community sectors and allows for response to urgent needs given the available resources. The document should be amended when circumstances change. For a natural hazard, “scientific information on an impending hazard must be transformed into a message to be acted upon, and a decision must be taken to warn affected people, who must then hear and react appropriately to the warning” (Alexander, 2015). However, a plan does not serve just to warn of impending hazard but also must follow through to ensure the well-being of a community. Specifically, if an evacuation is warranted, then leaders should weigh the positive and negative aspects of displacing a population, particularly because at times hazards have been used as an excuse to displace communities for deological purposes. Human lives and rights must always be at the forefront of emergency decision-making (Alexander, 2015).

A city’s resilience is contingent upon leadership, coordination, knowledge, communication, preparedness, and response amidst an environmental emergency. Table 2 details the key components of a resilient city. These criteria will be explored in the assessment of the resilience of the Canary Islands.
A Resilient City is one, where:

- There is strong leadership and coordination and responsibilities in disaster risk management are clearly delineated. This includes effective stakeholder engagement, well defined policies and strategies and distribution of tasks, effective lines of communication and mechanisms that facilitate effective risk management.

- The city is up-to-date on knowledge about hazards. Risk assessments are routinely prepared as a basis for urban planning and long-term development, including current and future investment decisions that contribute to improved resilience.

- There is an adequate financial plan that complements and promotes mechanisms to support resilience activities.

- Urban planning is carried out based on up-to-date risk information with a focus on the most vulnerable groups. Realistic and risk compliant building regulations are applied and enforced to effectively reduce physical risk.

- Natural ecosystems within and around the city’s territory are identified, protected and monitored to sustain and safeguard their protective functions as natural buffers.

- All institutions relevant to a city’s resilience are strengthened to have the capabilities they need to execute their roles.

- The social connectedness and culture of mutual help are strengthened through community, education, and multi-media channels of communication.

- There is a strategy to protect, update and maintain critical infrastructure to ensure that services continue and to increase resilience against hazards and the impacts of climate change.

- Effective disaster response is ensured by creating and regularly updating preparedness plans, connecting to early warning systems and increasing emergency and management capacities through public preparedness drills.

- Post-disaster recovery, rehabilitation, and reconstruction strategies are aligned with long term planning and provide an improved city environment after disaster events.

Table 2. List of the key components of a resilient city. From Gencer, 2017.
EMERGENCY EVACUATION PLAN OF THE CANARY ISLANDS: PEVOLCA

(Plan Especial de Protección Civil y Atención de Emergencias Por Riesgo Volcánico en la Comunidad Autónoma de las Canarias)

Would the Canary Islands be resilient in the event of a volcanic eruption? This section will dissect PEVOLCA, the Canary Island’s plan for a volcanic emergency, which came into existence as a result of seismic unrest in May of 2004. It now functions as a document that educates on and responds to volcanic observation, hazard, and evacuation.

The plan unites leaders across sectors in the case of a volcanic emergency. Specifically, management bodies hold executive power in decision-making, support bodies analyze the risk and make appropriate recommendations, operational coordination bodies maintain organization, and organizations of action intervene directly. Its objectives are stated in Table 3, and Figure 16 charts the organizations that would be mobilized in the case of a volcanic emergency, and their respective responsibilities.
The PEVOLCA PLAN has as a priority objective to establish the organization and procedures of action of public and private resources and services to deal with emergencies due to volcanic risk. This organizational framework should define, anticipate, and establish the following elements:

A. The organizational and functional structure for intervention in volcanic emergencies.

B. The mechanisms and procedures for coordination with the Plan State Civil Protection against Volcanic Risk, to guarantee its proper integration.

C. The systems of articulation with the organizations of the Local Administrations of their corresponding territorial scope.

D. The zoning of the territory according to the volcanic risk, delimit areas according to possible intervention requirements and locate the usable infrastructure, in support of the actions of emergency, in the event of volcanic risk.

E. The procedures for informing the population and its dissemination, and ensure its continuity through an educational process in the educational centers and social organizations.

F. The cataloging of specific resources and resources available to the planned actions.

G. The implementation and maintenance mechanisms to achieve effective operation of the Plan.

Table 3. Priority objectives of PEVOLCA, the volcanic emergency plan for the Canarian Archipelago. Translated from Gobierno de Canarias, 2010.
Figure 16: Flowchart of the management bodies, support bodies, operational coordination bodies, and organs of action that are invoked by PEVOLCA in the case of a volcanic emergency in the Canary Islands. Figure translated and adapted from Garcia de Canarias, 2010.
Plan of Action

While a Canarian can find solace in knowing that many organizations are prepared to respond to a volcanic emergency, it is also important that the islands’ residents understand their own duties. The implementation of PEVOLCA depends on the severity of the emergency but generally it progresses in the following manner:

1. Notification, assessment, and classification of the emergency.
2. Activation of the PEVOLCA Plan.
3. Emergency management.
4. End of the intervention. (Gobierno de Canarias, 2010)

Once the plan is activated, a system of alert is utilized to notify the public of the volcano’s condition. The three systems of alert: pre-alert (green), alert (yellow), and maximum alert (red) are explained below and by Figure 17.

**Green**

When the light is green, the officials who are designated in the action plan are expected to educate and raise awareness of the volcano’s behavior. Individual households are encouraged to have their own plans.

**Yellow**

Once the light transitions to yellow, citizens should listen to the radio for updates and prepare for an emergency by stocking up on medications, lanterns, and necessities. Individuals should cover food and water to avoid potential ash contamination.

**Red**

If the light becomes red, firstly, one should remain calm. Citizens should stay tuned for updates from local authorities and know the whereabouts of the members of
their household. At this stage, each citizen should pack a bag with clothing, toiletries, blankets, et cetera in case of an impromptu evacuation. This phase could last days to months. If there is volcanic ash, citizens must close doors and windows and be especially attentive to those are susceptible to upper respiratory disorders. Additionally, one should be cautious by wearing long sleeves, avoiding driving, and cleaning areas that may come into contact with the ash. Citizens who are evacuated from homes should take note of any cracks or gaseous smells upon return to their homes. If either is present, local authorities should be contacted immediately. One should refrain from using electricity or gas until the area has been checked.
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<th>Pre-emergent Phase</th>
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<td>Green</td>
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While the Canarian government website provides access to the entire PEVOLCA Plan, it is not an approachable document and realistically, is unlikely to be read through amidst a volcanic emergency. As a solution, the government webpage offers 6 bullet points of actions (additionally listed in Table 4) in case of a volcanic emergency. Still, these do not suffice as they drastically simplify the event. Hopefully, this document accurately and efficiently synthesizes and communicates the Canarian Plan of Action so that citizens and visitors make safe choices in the event of an eruption.

In summary, the Canary Islands conducts thorough volcano monitoring and does in fact have a detailed action plan in place but fails to connect these resources with the public. Positively, the Canary Islands demonstrates strong leadership and coordination of responsibilities in the case of volcanic emergency, scientific observation is up-to-date, and vulnerable infrastructure, ecosystems, and zones are noted. On the contrary, the archipelago could improve individual understanding of hazards, community education, and individual/community preparedness for emergency protocol. Although it is largely dependent on the circumstance of the crisis, there should be clarification on evacuation. To where would individuals be evacuated? It is unclear how the warning system is communicated to citizens. The plan expects that individuals listen to the radio for updated information. Is there another, more effective method for communication? Additionally, individuals would be more prepared for a volcanic emergency if they were to receive an orientation on volcanic hazards and the Canarian Plan of Action, and if they were to participate in a large-scale preparedness drill. These could be made mandatory or be monetarily incentivized. This analysis does not speak to the Canary Island’s procedures for financial recovery post-eruption.
Volcanic eruptions tips

The Canary Archipelago is formed by a set of islands of volcanic character, which although tectonically is stable, can undergo seismic movements or volcanic eruptions if an eruption is announced.

Table 4. Advice from the Canarian government in the case of a volcanic eruption.

- Do not approach the volcano (not slag or solid products may reach you).
- Avoid approaching areas declared hazardous to facilitate evacuation tasks.
- If you are surprised by a cloud of gases, protect yourself with cloth moistened with water.
- Avoid hollows because harmful gases accumulate.
- If possible, do not reach areas declared hazardous for the evening hours or at night.
- Mount a battery-powered radio and a mobile phone with you.
- Carry a first aid kit (绷带, snowy, bandages, antiseptic, painkillers).
- Keep a guide on the island, personal medicine, and food.
- If the authorities establish the evacuation, prepare a light day bag with warm clothes, identification documentation of the whole family, personal medicines, and, if possible, non-perishable food.
INTERNATIONAL VOLCANOLOGY COMMUNITY

For individuals who are looking to self-educate and for communities that are seeking educational resources, there are several organizations that provide information on global volcanoes. Their websites are helpful in relaying updates on volcanic activity and hazards. In the case of a volcanic emergency, some of these organizations can dispatch assistance and provide water, shelter, and protective gear.

International Association of Volcanology and Chemistry of the Earth’s Interior (IAVCEI)

The *International Association of Volcanology and Chemistry of the Earth’s Interior* (IAVCEI) researches volcanoes to mitigate their risks (IAVCEI, 2017). Table 5 lists the organization’s objectives.
1. To study scientific problems related to volcanoes and volcanic processes, past and present, and to the chemistry of the Earth's interior.

2. To encourage, initiate and coordinate research, and promote international cooperation in these studies.

3. To encourage volcanologists to alert appropriate authorities about the importance of adequate surveillance of active volcanoes and potentially active volcanoes, and of volcanic risk assessment.

4. To arrange for the discussion and publication of the results of scientific research on volcanology and on the chemistry of the Earth's interior from IAVCEI.
**World Organization for Volcano Observatories (WOVO)**

The World Organization for Volcano Observatories (WOVO) is “an organization of and for volcano observatories of the world. Members are institutions that are engaged in volcano surveillance and, in most cases, are responsible for warning authorities and the public about hazardous volcanic unrest” (WOVOdat, 2017). To do so, WOVO facilitates communication between institutions responsible for volcano monitoring, maintains data reported on monitored volcanoes, and connects governments and observatories (World..., 2017). WOVO publishes information about volcanic unrest on a comprehensive, global database known as WOVOdat (WOVOdat, 2017).

**Volcano Disaster Assistance Program (VDAP)**

The Volcano Disaster Assistance Program came to fruition in response to the 1985 Nevado del Ruiz eruption in Colombia, where 23,000 people were killed. VDAP is a partnership between the USGS and U.S. Agency for International Development’s Office of U.S. Foreign Disaster Assistance. Since its establishment, VDAP has responded to 30 crises and assisted hundreds of volcanic events. While VDAP has not assisted with any volcanic emergencies in the Canary Islands, it has assisted with a crisis in Cape Verde after the Fogo Volcano, a volcano of similar activity and environment to el Teide, erupted. VDAP has bolstered response plans in 12 countries (USGS-VDAP, 2017).

**USGS Volcano Hazards Program**

In the United States, the Volcano Hazards program disseminates monitoring information and educates the public on volcanic emergency preparedness. The organization recommends that individuals living in volcanic hazard zones make a plan
that accounts for all household members and identifies supplies such as food, water, a flashlight, and a first aid kit that should be included in a survival kit (USGS: Volcano., 2017).

**RESPONSE TO VOLCANIC ERUPTIONS**

The International Federation of Red Cross and Red Crescent is a humanitarian network that responds to natural disasters and health emergencies, and strengthens the resilience of affected communities. Following a disaster, the organization releases Emergency Plans of Action that summarize the situation itself, and the response and strategy necessary to mitigate the situation and ensure the safety of the affected communities. The plans provide in depth analyses of actions, targeted results, and finances. This section will dissect the action during and following three recent eruptions: Mount Kelud, Chaparrastique, and Fogo. Images of the eruptions are in Figure 18. All three volcanoes are stratovolcanoes like el Teide and two of the three are island volcanoes. Since Tenerife has not experienced an eruption since the establishment of PEVOLCA, this section will highlight three examples that show how monitoring, the emergency action plan, and recovery post-eruption coincide and ultimately reduce fatalities, as well as the weaknesses of each response.

**Mount Kelud, Indonesia**

On February 13, 2014, Mt. Kelud erupted. Eleven days prior to the eruption, The Indonesian Volcanology and Geology Disaster Mitigation Center changed the volcano’s status from Normal to Aware. This status was changed, to Alert, 8 days later. Then, only two hours before its eruption, Mt. Kelud’s status was elevated to Danger. Declaring the
volcano’s activity in the Danger zone immediately prompted an evacuation of individuals living within 10km of the crater. The eruption produced plumes that rose 19km and projected ash and stones. The volcanic ash traveled 250km and affected 18 regions and 7 airports. Indonesia’s president invoked an emergency response that called upon local governments and the National Disaster Management Agency (International..., 2014b).

The day after the eruption, there were 7 fatalities, 70 hospitalizations, and 100,248 internally displaced persons. By February 18\textsuperscript{th} (five days after the eruption), the number of internally displaced persons in the evacuation camps decreased to 83,088. In addition to the erupted products, heavy rains caused cold lahar flooding in several districts (International..., 2014b).

The disaster response centered on three groups with the focuses of 1) return of internally displaced persons, 2) security and safety of community, 3) improvement of houses, infrastructure and facilities. In the meantime, the camps for internally displaced persons offered public kitchens, clean drinking water and relief items; specifically, 500,00 masks, 4,000 sleeping mats, 1,500 hygiene kits, 1,500 tarpaulins, and 500 baby kits. Additionally, there were five water trucks and 7 ambulances for medical assistance. Government departments focused their efforts on the supply of clean water, the removal of volcanic debris from homes, the distribution of protective equipment, and the provision of shelter (International..., 2014b).

The Mt. Kelud Emergency Plan of Action post-eruption was a two-month operation that aimed at assisting 16,500 people (3,400 families). To accomplish this, 400 volunteers were called upon to assist with government efforts and the project was allocated the equivalent of 242, 601 USD (International..., 2014b). The economic losses
totaled to about 88.6 million USD. Like the procedure in the Canary Islands, Mt. Kelud had a warning system prior to its eruption, invoked government leaders, and addressed similar priorities to those in PEVOLCA. The response to the Mount Kelud eruption demonstrates how monitoring allowed officials to effectively forecast an eruption and execute an evacuation of vulnerable individuals (within 10km of the crater) in a timely fashion.

**Chaparrastique, El Salvador**

The Chaparrastique Volcano in El Salvador erupted on December 29, 2013. The eruption ejected ash and gas five kilometers into the air, affecting 63,079 individuals in the principalities of Chinameca, San Jorge, San Rafael Oriente, and El Tránsito. The first eruption emitted 637 tons of ash, which increased to 2,200 tons. Emitted sulfur dioxide reached 20 parts per million following the eruption, which is lethal when exposure surpasses 30 minutes (International..., 2014a).

Emergency responders prioritized the provision of healthcare and emergency evacuation, the distribution of safe water, community and family sanitation and hygiene, and the protection of livelihoods, especially livestock and farm animals. Wind carried ash to communities, posing a threat to lung, eye, and skin health. For 62 days, a first aid station and two ambulances provided care to 270 people. One hundred and twenty nine people received first aid training and 1,314 families attended healthcare promotional campaigns. Additionally, 7,215 respiratory masks, 400 hygiene kits, and 1,000 clean up kits containing a shovel, a broom, goggles, gloves, masks, and trash bags were distributed. Four hundred and fifty five families received food for cattle and 363 cows were vaccinated (International..., 2014a).
The National Civil Protection, its corresponding committees, 2,400 volunteers, and 230 staff members responded to the Chaparrastique eruption. The four-month operation was allotted a budget of 151,161 USD and aimed to assist 5,000 out of 63,079 affected individuals. While teamwork and collaboration facilitated a smooth response, water supply was limited and sporadic and some communities were left without water for 21 days (International..., 2014a). The Chaparrastique eruption shows the impact of an eruption on human health and surrounding agriculture. The Canary Islands can learn from this response’s failure to provide adequate clean water.

**Fogo, Cape Verde**

The Fogo Volcano in Cape Verde erupted on November 23, 2014. It produced lava flows that destroyed 230 buildings, 445 hectares of land, and obliterated the communities of Bangeira and Portela. Fortunately, no lives were lost but 1,076 people were displaced and at the time of the assessment 1,500 people were projected to need further assistance (International..., 2015).

The government arranged three camps for evacuation that distributed sheets, buckets, clothes, food, glasses, medication, hygiene kits, and other essential supplies. The Emergency Action Plan invoked a Rapid Assessment Team, a National Disaster Management Coordination Team, and mobile/local coordination teams (International..., 2015). The Red Cross of Cape Verde responded to the eruption of the Fogo Volcano and aimed to assist 2,500 individuals (500 families). The operation lasted for 6 months, received a budget of 120,296 USD, and involved a total of dozens of organizations (International..., 2015). This example demonstrates how an explicit plan and
understanding by involved sectors of their responsibilities can minimize fatalities and optimize response.
Figure 18. a) February 13, 2014 Mount Kelud eruption in Indonesia (Rozario). b) December 29, 2013 Chaparrastique eruption in El Salvador (Quiñones et al., 2013). c) November 23, 2014 Fogo eruption in Cape Verde (In pictures).
CONCLUSIONS

Volcanology is in its infancy; twenty-five years of monitoring are miniscule compared to Tenerife’s 11.9 million year history. In an uncertain field, it is imperative that scientists, government leaders, and community members take all of the actions that are available to minimize risk. Through routine monitoring of geochemistry, seismicity, and land deformation, a volcanic eruption can be more accurately forecasted. This, coupled with the establishment of an emergency action plan, significantly increases the preparedness and safety of a community. In the case of Tenerife, scientists routinely monitor volcanic activity and have partnered with government officials to institute an emergency plan of action. Yet, a detrimental disconnect exists between the monitoring and the general awareness. This gap must be bridged to facilitate a tranquil and efficient response in the event of a volcanic emergency. A smooth transition from scientific monitoring to general action is essential to protect human lives, livelihoods, and infrastructure. Through the union of volcano monitoring, emergency preparation, and public education, humans can exist in the shadow of volcanoes.
ACKNOWLEDGEMENTS

This project was inspired by a geochemical volcano monitoring summer internship with the Instituto Volcanológico de Canarias (INVOLCAN) of el Instituto Tecnológico y de Energías Renovables in Tenerife, Canary Islands. There, I learned the mechanisms and science of volcanic observation and upon returning to the United States, I became interested in how this information translates to the public. Thank you to INVOLCAN for inspiring this curiosity in me and especially to Dr. Fátima Rodríguez for sharing her knowledge with me, and to Geraldine Regnier for bringing endless enthusiasm to the field and lab. Thank you to those who have supported me throughout this project: Thank you to Dr. Mary Savina at Carleton College, who advised me throughout this process and my time at Carleton, and to Dr. Bereket Haileab for first exposing me to geochemistry and encouraging me throughout my time as a student of geology. Thank you to Emma Link for revising a draft of my comprehensive project and for providing me with thorough feedback. Thank you to the Towsley Foundation, the Science Board, and the Carleton College Geology Department for funding my attendance at the American Geophysical Union Fall Meeting to present the abstract that was generated from this summer’s research at INVOLCAN. And to my family, thank you for the endless opportunities and support.
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