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THE 2009 AND 2011 HAZARD EVENTS AT SAN VICENTE VOLCANO, EL SALVADOR: VULNERABILITY, RESETTLEMENT, AND DISASTER RISK REDUCTION

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THE 2009 AND 2011 HAZARD EVENTS AT SAN VICENTE VOLCANO, EL SALVADOR: VULNERABILITY, RESETTLEMENT, AND DISASTER RISK REDUCTION

By

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Dedication:

To my family, my friends, and my colleagues in El Salvador.

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Chapter 2. University contributions to risk reduction in a post-disaster context: A case study of reorienting research efforts at San Vicente volcano, El Salvador

This chapter has been submitted to a special paper of the Geological Society of America, titled, “Geoscience for the Public Good and Global Development.” This manuscript incorporates edits from three external reviewers. L. Bowman conducted interviews and participant observation, coded qualitative data (interviews, field notes, and documents), translated Spanish quotations into English, and drafted the manuscript. J.S. Gierke helped develop the thesis of the manuscript, organize and edit the written text, and situate our work within the evolution of DRR in San Vicente. J.F. Cruz provided information regarding the role of UES-FMP in San Vicente, as well as, an account of DRR progress in the region since L. Bowman’s departure in 2012.

Chapter 3. Disaster risk reduction and resettlement efforts at San Vicente (Chichontepec) Volcano, El Salvador: toward understanding social and geophysical vulnerability

This paper was published in the Journal of Applied Volcanology and is written by L. Bowman and K. Henquinet. L. Bowman conducted all interviews and participant observation, coded qualitative data (interviews, field notes, and documents), translated Spanish quotations into English, and drafted the manuscript. K. Henquinet helped with the research design and development of the interview guide, as well as manuscript organization, thesis development, and writing. All authors read and approved the final manuscript.

Chapter 4. Interpreting saturation changes as a potential factor in shallow, rainfall-induced landslides from time-lapse seismic refraction, San Vicente Volcano, El Salvador

This manuscript is in preparation to be submitted. L. Bowman organized logistics for the field work in El Salvador, conducted field work, aided in data processing and interpretation, and wrote portions of the manuscript. J.P. Richardson conducted field work, processed and interpreted data, generated figures, and developed portions of the manuscript. J.S. Gierke proposed the research, conducted field work, interpreted data, and developed and revised the text.

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Abstract

Scientists from a variety of disciplines have made major advancements in the geophysical and social aspects of hazard science. Despite these advancements, economic losses and the number of people affected by disasters continue to rise. The field of disaster risk reduction (DRR) attempts to counter this rising trend of disaster losses by integrating a variety of disciplines to holistically solve complex problems related to risk and vulnerability. Frequent disasters in El Salvador provide insight into the evolution of DRR and its application during and after two hydrometeorological disasters in the department of San Vicente in 2009 and 2011. This dissertation is divided into four chapters beginning with a unifying introduction that describes contextual background details about DRR policy and why El Salvador was chosen as a field site. Chapter 2 uses qualitative research methods like participant observation, semi-structured interviews, and document review to analyze the evolution of DRR in San Vicente and highlights the unique role of the Universidad de El Salvador – Facultad Multidiscplinaria Paracentral in directing new research and training programs toward reducing disaster risk. Chapter 3 uses similar ethnographic methods within the heavily damaged community of Verapaz to analyze local residents' perceptions of a relocation scheme designed to reduce physical vulnerability to debris flows. This publication demonstrates that aspects of social vulnerability were not adequately considered, as the majority of homes deemed "uninhabitable" continue to be occupied by residents, but residents who received a new home have developed unanticipated strategies to diversify livelihoods and reduce risk to disasters. Chapter 4 describes a concerted effort to improve our understanding of slope stability and shallow landslides using time-lapse seismic refraction methods. Data acquired during two field campaigns demonstrated survey repeatability and a validation of methods used, however saturated layers and perched water tables, which were hypothesized to be a contributing factor to rainfall-induced landslide generation, were not able to be imaged. The four chapters of this dissertation touch on important aspects relevant to local communities and institutions living and working in San Vicente where landslides, debris flows, and flooding have affected the region. The interdisciplinary

nature of this research incorporates the voices, personal experience, and expertise of academics, community members, institutional representatives, politicians, and DRR practitioners in an attempt to holistically address the pressing concern of recurrent natural hazards for the region around San Vicente volcano.

Chapter 1: Introduction

Scientists from a variety of disciplines have made major advancements in the geophysical and social aspects of hazard science. Determining hazard magnitudes, distribution, probabilities, recurrence intervals, and even forecasting have all improved over the last several decades. Similarly, an improved understanding of the dimensions of risk and vulnerability have triggered new strategies to reduce disaster risk by transitioning focus from the geophysical factors that trigger a hazard event to the social-structural causes that perpetuate and institutionalize human vulnerability.

Despite these technological and scientific advancements, economic losses and the number of people affected by disasters continue to rise (Keen et al. 2003). Global population growth and increased development are contributing factors in these trends; however, the changing demographic and socioeconomic characteristics of highly urbanized communities located in hazardous regions, along with increased extreme weather events, are mostly responsible for the documented increase in disaster losses (Donner and Rodriguez 2011; Public Safety Canada). The frequency of recorded disasters have risen from about "100 per decade during the period 1900 – 1940; 650 per decade in the 1960s; 2000 per decade in the 1980s; and reaching almost 4800 per decade in the 1990s to more than 7200 in the 2000s (IRDR 2013). Part of this increase in frequency and magnitude of disasters can be attributed to human-induced climate change—particularly weather-related events like storms and floods (IPCC 2007; Bouwer et al. 2007). Though the number of people killed by disasters has begun to decrease due to better forecasting and warning, there are rising numbers destroyed livelihoods and adverse economic impacts. "Since 1997, there has been a several-fold increase in weather-related economic losses" (ICSU 2008: 9).

In 2010, El Salvador was ranked as the country the most vulnerable to natural hazards in the world (UNDAC 2010). Their colonial history, geography, socioeconomic marginalization of the poor, and a statewide shift toward neoliberal development policies has created a state that shifts development and disaster risk reduction responsibilities to non-governmental organizations, while at the same time reaping the benefits from

continued foreign disaster aid for reconstruction after disasters that is not adequately invested in disaster reduction or preparedness (Anderson and Woodrow 1989 *from* Tellman 2011; Schipper and Pelling 2006; Wisner 2001).

This dissertation draws from recent disasters in El Salvador to show that insufficiently addressing the underlying, root causes of vulnerability perpetuates high risk levels for Salvadorans, which exacerbates disaster losses. Despite many scientific, technological, and development efforts, rural Salvadorans continue to be threatened by natural hazards.

The research is framed around two disasters at San Vicente Volcano in 2009 and 2011and provides insight into how disaster risk reduction and research has evolved in the region. The design and implementation of a relocation scheme highlights dimensions of the underlying causes of social and physical vulnerability as they relate to volcanic and hydrometeorological hazards. A multi-institutional effort to better understand the geophysical triggers of shallow landslides and debris-flows (lahars) was undertaken to improve slope stability monitoring and hazard preparedness for the region.

1.1 Disasters and development

Natural disasters are often viewed as unpredictable events that humans cannot control. Most efforts related towards disaster research are directed at studying the physical hazards that cause disasters or the capacity for engineered mitigation projects to reduce disaster risk. These efforts receive the most focus *after* a disaster occurs when the impacts are highlighted by media and of particular interest for donor and research institutions. It has long been thought that a more complete understanding in the field of hazard science would eventually reduce risk to hazards and decrease the number of disasters (Oliver-Smith and Hoffman 1999; Smith 2013). There is a global promotion of sustainable development aimed at empowering communities and reducing poverty, which would seem a natural step to reduce societies' exposure to hazards; however, global disaster risk continues to increase (Thomalla et al. 2006).

Figure 1 shows the increase in the number of recorded disasters from 1900 – 2011. Figure 2 shows the rising costs of disaster impacts from 1975 – 2011. Part of this

rise is artificial due to better reporting by agencies like USAID and the Red Cross; however, roughly two-thirds of the rise is real due to increased hydro-meteorological events affecting increasingly vulnerable populations (Than 2005). Though the number of fatalities has decreased during the last decade, the number of individuals adversely affected continues to rise.

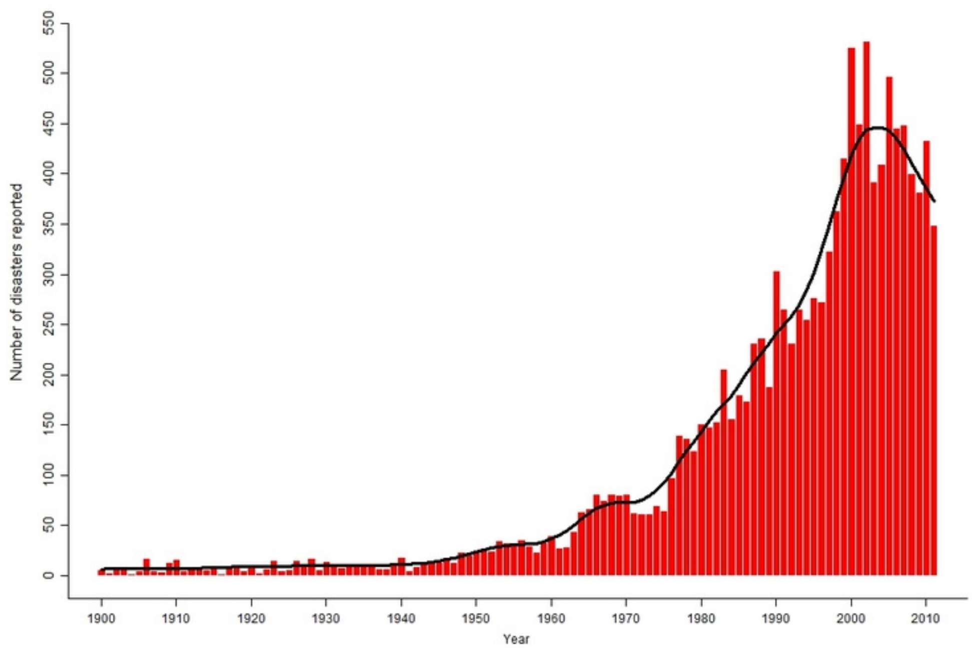

Figure 1.1 Number of recorded disasters from 1900 – 2011 (Modified from EM-DAT 2011).

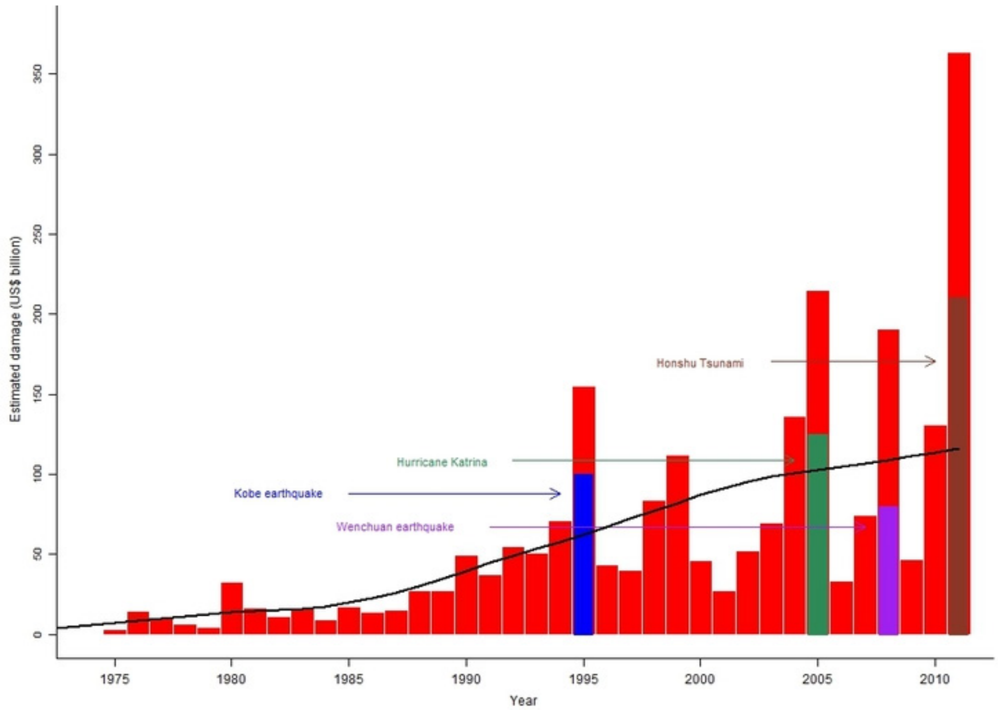

Figure 1.2 Estimated damages (US $billion) cause by reported disasters 1975-2011 (Modified from EM-DAT 2011).

Evidence shows that disasters are becoming more frequent due to climate change and a higher concentration of the world's growing population residing in hazardous areas (Keen et al. 2003; IPCC 2012). Hydro-meteorological hazards related to climate change affect an increasing number of people and economies (Thomalla et al. 2006). In 1980, roughly 100 hydrometeorological disasters were reported, but by 2000 that number increased to 300/year and continued to rise (*Guha-Sapir* from Than 2005). From 2000 to 2011, the impacts of disasters globally totaled US$1.7 trillion in damage, 2.9 billion individuals affected, and 1.2 million people killed (UNISDR 2013). Not only is the frequency of disasters increasing, but human "vulnerability is also increasing due to rising poverty, a growing global population, armed conflict and other underlying development issues" (Schipper and Pelling 2006). The relationship between development activities, increasing vulnerability, and the rise in number and magnitude of disasters supports the need for research into disaster risk reduction and management.

Anthropological work directed toward hazard and risk has created wider recognition of the root causes that create human vulnerability and that disasters are, in

fact, part of "the normal order of the things, that is, the conditions of inequality and subordination in the society rather than the accidental geophysical features of a place" (Oliver-Smith 2009). Especially over the last 30 years, researchers and practitioners have explored and promoted the notion that disasters are not "random acts of God" but rather a confluence of nature and social structures (Hewitt 1983; Oliver-Smith and Hoffman 1999; Lewis 1999). Societies, communities, and nations are structured and develop in ways that expose humankind to natural occurring phenomena that systemically foster the conditions that exacerbate the impacts of hazard events. Additionally, the poorest and most disadvantaged populations suffer the greatest consequences when hazard events occur. "Today it is acknowledged that those affected by disasters tend to be people who are marginalized in three ways; geographically, because they live in marginal, hazard-prone areas; socially, because they are poor; and politically, because their voice is disregarded" (Gaillard et al. 2007; Mercer 2008).

A paradigm shift away from traditional "disaster response" towards state investment in disaster risk reduction (DRR) has slowly worked itself into governmental policy. Traditionally, disasters were "managed" through reactionary responses to the aftermath (i.e., search and rescue; provision of shelter, food, medical care, reconstruction, etc.) and responding to affected populations' needs. These response efforts are vital but insufficient without consideration of reducing vulnerability and risks for the next events. The Haitian earthquake in 2010 (which killed ~160,000 people) highlights the disparity between effective DRR and disaster response: "After 11 days of intense effort of 43 rescue teams supported by roughly 2000 US soldiers…133 persons were rescued alive from the rubble," which stirs Oliver-Smith (2013: 2) to ask how many more thousands could have been saved, "if adequate resources and efforts were invested in development policies and practices that factored in exposure, risk and social vulnerability?"

El Salvador is another prime example of a country where the focus is on response rather than risk reduction. Approximately US$4 million is invested each year in El Salvador for disaster prevention. Yet the nation received about US$150 million in 2011 after Tropical Depression 12E (Tellman 2011) and almost none of the aid went to risk

reduction even though rain-induced hazards (flooding and landslides) are almost annual occurrences.

Examples like Haiti and El Salvador show how a reliance on disaster management and reconstruction is insufficient since it does not effectively address socially constructed vulnerability (e.g., Oliver-Smith 2013; Wisner 2001; Barton 2015; Tellman 2011; Bowman and Henquinet 2015). Similar results from other cases have helped shift responsibility from disaster management approaches and disaster responders to the planners, scientists, development experts, and governments that invest in preparedness, education, monitoring, and pre-disaster planning—all tenets of DRR. The continuing rise in economic costs and lives impacted shows that this transition takes time, investment, and political will to counter current trends.

1.2 Disaster Risk Reduction and Development

Disasters hinder development by disrupting livelihoods. Many response-focused agencies have evolved to broadening their energies towards preparedness and education initiatives to transmit hazard information. Paton (2000: 1) asserts, “while public education programs may be successful in promoting awareness, additional interpretive processes influence whether a threat is accepted and whether the person acts to reduce this risk.” In many cases where outreach efforts have been applied, education and increasing hazard awareness alone does not decrease the number or severity of disasters. Integrating a participatory approach that incorporates at-risk populations within the research process and veering away from passive learning strategies is an underexplored method to create a more lasting impact on at-risk populations and their behavior during emergencies.

The need for a new approach to natural disaster reduction was highlighted by the United Nations’ Declaration of the International Decade for Natural Disaster Reduction (IDNDR). This strategy was developed in the late 1980s to foster “international cooperation in the field of natural disasters reduction” to be implemented throughout the 1990s (Lechat 1990: 2). At the onset of the IDNDR, Lechat (1990) idealized that “recent breakthroughs in knowledge and advances in technology now make it possible to

envisage a large mobilization of resources in order to reduce the tragedy of natural disasters."

The IDNDR was an important first step in outlining specific goals for: 1) improving the capacity of countries to mitigate the effects of natural disasters, 2) devising appropriate strategies to apply existing scientific and technical knowledge, 3) fostering scientific and engineering endeavors, 4) disseminating knowledge, and 5) monitoring and evaluation of disaster reduction efforts (Lechat 1990). Unfortunately, a reduction in disasters did not occur (United Nations 1999). At the end of the IDNDR, the United Nations lamented: "despite a decade of dedicated efforts, the number and costs of natural disasters continue to rise, given the increasing vulnerability of our societies to natural hazards" (United Nations 1999). The 10-year-long strategy steered new investment and research toward DRR but did not achieve its desired goals. At the effort's conclusion, it was stated that "more than ever there is a need to strengthen and broaden disaster prevention programs and, above all, to obtain political commitment…for a proactive management of risk and application of science and technology at all levels to mitigate the impact of natural disasters" (United Nations 1999). The UN's dedication to continued investment in DRR was made apparent through later efforts detailed below.

Reducing disaster risk is vital for sustainable development, especially in developing nations (Schipper and Pelling 2006). The socioeconomic dimensions of disaster risk reduction are intricately linked to development, as pointed out by Oliver-Smith (2013: 2): "Risk and vulnerability are in large measure the products of historical and existing processes of social and economic development." For example, the development realities in Indonesia show the interrelated nature of development and disasters. As population grows, subsistence farming methods and land-use changes cause deforestation and the need for more roads (Coca 2015). These changes represent steps taken to facilitate economic development in impoverished, rural areas. However, these steps toward development have consequences related to slope stability. Landslides, which are increasingly prevalent due to human-induced landscape and climate change, now account for more combined deaths in Indonesia than tsunami, volcanic eruptions, and earthquakes (Coca 2015).

Effective disaster preparedness and risk reduction should provide citizens with tools, knowledge, and institutional support to survive hazard events with little disruption to livelihood activities and social networks. Successful disaster risk reduction schemes plan for both the potential physical impacts of a hazard event and the socio-economic and cultural implications for the affected population. Disaster risk reduction also achieves broader success when designed and implemented with input from the affected population alongside expert planners and authorities. Many cases have successfully incorporated local/indigenous knowledge in designing culturally appropriate risk reduction efforts (Cronin et al. 2004; Mercer et al. 2007; Mercer et al. 2008; Mercer et al. 2009; Németh and Cronin 2009). Finally, DRR should focus not only on reducing physical exposure to hazards but also strive to address the "root causes" of social vulnerability that perpetuate risk to natural hazards (Wisner 2001).

While disaster risk reduction is inherently linked to sustainable development, DRR is not necessarily a product of development. The current situation of high vulnerability and risk can be attributed to development initiatives that place unfair strains on the poorest populations. Oliver-Smith (2013: 2) asserts that, "Many of the processes that drive risk and vulnerability are standard development strategies." There are many challenges ahead and a long history of "the way things have always been done" to get beyond. Mercer et al. (2008) explain that while

> "disaster risk reduction research has steadily developed, strategies implemented to reduce risk often continue to operate in a top-down fashion, ignoring social dynamics, [and] vulnerability is not reduced because 'at-risk people are not made visible, are not reached or are not included in decision-making processes."

Recognizing the aforementioned challenges to integrate DRR and development spurred the United Nations to incorporate DRR into the design of development goals outlined and adopted in 2000 (United Nations 2000; Pelling et al. 2004). Since 2000, DRR strategies have been revisited and revised with new directives by evolving DRR think tanks.

1.3 United Nations Development Efforts

1.3.1 Millennium Development Goals (MDGs)

The realization that disasters hinder development and that integrating DRR into development is extremely difficult spurred the United Nations International Strategy for Disaster Reduction (UNISDR) to detail further efforts and new methodologies to improve the incorporation of DRR into development plans in order to meet the MDGs. After the conclusion of the IDNDR, the United Nations issued its Millennium Declaration establishing the following eight development goals in 2000:

1) Eradicate extreme poverty and hunger
2) Achieve universal primary education
3) Promote gender equality and empower women
4) Reduce child mortality
5) Improve maternal health
6) Combat HIV/AIDS, malaria and other diseases
7) Ensure environmental sustainability
8) Establish a global partnership for development (United Nations 2000)

These "Millennium Development Goals" (MDGs) were to be achieved by 2015 and provided the framework used by most development institutions since the Declaration. The strategic plan includes DRR components as it "seeks to reduce the number and impacts of disasters" by achieving these goals (UN 2000; Schipper and Pelling 2006). The Declaration not only states the importance of reducing hazards, but also outlines specific DRR actions to achieve its Millennium Development Goals (MDGs). These include:

1) Develop early warning systems
2) Develop vulnerability maps
3) Promote research into the causes of disasters

The eight MDGs promulgated in 2000 are widely viewed as achievable by development institutions. Schipper and Pelling (2006) stressed that incorporating the tenets of disaster risk reduction into the MDGs is key in order to fully meet the objectives in a sustainable manner. The MDGs have achieved some criticism due to the conflictive relationship between development and disaster risk reduction efforts. Critics of the MDGs (Attaran 2005; Bendaña (2004, loc. cit. Schipper and Pelling (2006)) are

concerned that a narrow focus and interpretation of the MDGs limits the integration of disaster risk reduction into broader development plans.

1.3.2 Hyogo Framework for Action (HFA)

The 2005 World Conference on Disaster Reduction (WCDR) in Kobe, Japan resulted in the Hyogo Framework for Action 2005-2015 (HFA): Building the Resilience of Nations and Communities to Disasters—a 10-year plan to reduce disaster risk by promoting more sustainable development in both nations and communities designed by the UNISDR program. It is the first plan of its kind to "explain, describe, and detail the work that is required from all different sectors and actors to reduce disaster losses" (UNISDR 2015a). The plan specifies that disaster risk is a global concern that is

> "compounded by increasing vulnerabilities related to changing demographic, technological and socio-economic conditions, unplanned urbanization, development within high-risk zones, under-development, environmental degradation, climate variability, climate change, geological hazards, competition for scarce resources, and the impact of epidemics" all of which "points to a future where disasters could increasingly threaten the world's economy, and its population and the sustainable development of developing countries" (UNISDR 2005).

The advancements made during the decade-long program towards "knowledge, practice, implementation, experience, and science for disaster risk reduction" inspired the United Nations General Assembly to pass a subsequent resolution to further refine appropriate strategies beyond the year 2015 (UNISDR 2015b). This post-2015 Framework was recently proposed during the 3rd World Conference on Disaster Risk Reduction in Sendai, Japan in March 2015, which represents a growing acceptance that DRR is a priority and that the strategies to achieve global goals are constantly evolving.

1.3.3 Integrated Research on Disaster Risk (IRDR)

In 2005, an assessment by the International Council for Science (ICSU) stressed that one of the great challenges to development is "the widening gap between advancing science and technology and society's ability to capture and use them" (ICSU 2005). Likewise, increasing disaster impacts in both developed and developing countries

suggests that reducing hazard risk through economic growth and current development policy will not alone reduce disaster losses. These realizations spurred the ICSU, UNISDR, and the International Social Science Council (ISSC) to design a decade-long plan (2008-2017)—Integrated Research on Disaster Risk (IRDR)—aimed at:

1) Characterizing hazards, vulnerability, and risk
2) Understanding decision-making in complex and changing risk contexts
3) Reducing risk and curbing losses through knowledge-based actions (ICSU 2008)

After 10 years, IRDR aims to see a reduction in disaster losses when compared to similar hazards events prior to 2008. IRDR is a key partner in the United Nations efforts and helped construct the frameworks used throughout the international community. One advancement has been a new IRDR strategy to integrate science into DRR policy. Teams of researchers and “specialists from any and all relevant fields” now develop Forensic Disaster Investigations (FDIs) to study specific disaster cases in order to “probe more deeply into the complex and underlying causes of growing disaster losses” (Burton 2010: 36).

FDIs are not meant to blame entities or individuals for weaknesses that exacerbate disaster impacts since responsibilities, but rather highlight ways in which previous systems can be modified in order to prevent future disaster losses. Disaster impacts rarely are the responsibility of a single person or institution, as social vulnerability and exposure to hazards are conditions structured by societal and political systems. The goal of the FDIs is to promote a cultural paradigm shift that allows institutions and governments to explore a new discourse that recognizes and addresses the structural weaknesses that lead to vulnerability, rather than solely focusing on disaster response and reconstruction.

The FDI framework defines four research methodologies that draw from interdisciplinary fields to “provide a mechanism for developing better comparative understandings of the root causes and underlying process that lead to disaster risk in diverse socioeconomic, cultural, national, regional, and local settings” (Burton 2010: 40). This effort represents the latest project design in a long evolution of DRR strategies that shift focus from the geophysical triggers of the disaster and offer an assessment of the structural causes of disasters.

All of these aforementioned initiatives demonstrate a global shift in attitudes on how best to design and implement disaster risk reduction. Rising disaster losses plainly show that changing rhetoric does not alone reduce risk, however nor do the traditional strategies of disaster management and reconstruction. Globally accepted frameworks designed by experts from many fields, however, now address root causes of vulnerability. Most importantly, acceptance and endorsement of these frameworks by donor countries and institutions like the United Nations, World Bank, and International Monetary Fund could help pressure and guide countries that receive aid to invest more in disaster risk reduction rather than disaster symptoms.

1.4 Dissertation Problem Statement and Objectives and Motivation

The design of my doctoral research integrates two interconnected interests: (1) the geological and hydrometeorological phenomena that trigger hazard events, and (2) the desire to better prepare at-risk communities to reduce disaster impacts. After having spent two years volunteering in the U.S. Peace Corps in Honduras, one year of which was during the most active hurricane seasons on record (2005), I saw first-hand how natural hazard processes intrude upon, and often overcome the capacities of, rural communities that are ill-prepared for natural hazards (Trenberth and Shea 2006).

I enrolled in graduate studies at Michigan Technological University in 2007 to receive academic and professional training that would allow me to blend my interests in geological hazards with field research in Latin America. I conducted my M.S. research within a Salvadoran community for five months, analyzing disaster prevention and mitigation measures implemented by an NGO at Santa Ana volcano, El Salvador (Bowman 2009). Three weeks after defending my M.S. thesis in October 2009, the Hurricane Ida lahar disaster occurred on the northern slopes of San Vicente volcano in El Salvador. Initial reports by media and colleagues on the ground described poorly prepared communities, no warnings nor preventative evacuation measures, and lackluster institutional support and coordination. News of this event solidified my goal to return to

El Salvador to apply important lessons learned at Santa Ana volcano and expand into new, exploratory research activities in this post-disaster setting.

In 2011, I proposed a research plan to the U.S. Fulbright Student Scholar program, titled, "Developing Culturally Appropriate Disaster Risk Reduction Strategies in El Salvador," which provided support for a nine-month-long field season. At the same time, the Agricultural Sciences department at the Universidad de El Salvador – Facultad Multidisciplinaria Paracentral campus in San Vicente formally requested a U.S. Peace Corps Response volunteer to assist the University with disaster prevention and mitigation activities. Both projects' objectives were well-aligned (see Chapter 2), and I was accepted for both positions, resulting in a 15-month-long period working alongside communities and institutions in DRR.

My work integrates two disciplines—geology and anthropology—to provide a holistic understanding of how communities prepare for natural hazards. In order to understand and reduce natural hazard impacts, it is necessary to integrate a geological understanding of hazard triggers with a socio-cultural understanding of the population at-risk.

My research premise was articulated best in June 2010, when scientists from the Volcano Disaster Assistance Program (a USGS/USAID Office of Foreign Disaster Assistance joint effort) provided technical advice to the Salvadoran hazard-monitoring agency, Servicio Nacional de Estudios Territoriales (SNET), concerning the November 2009 disaster at San Vicente Volcano (Schweig 2010). Along with a better characterization of slope stability, the team recommended more sustained and robust outreach efforts with the at-risk population in order to reduce disaster risk.

> "An active education and outreach program is critical for reducing the loss of life and property from landslides and debris flows. Such a program should focus on the population potentially at risk from these hazards. It should provide enough information to give them an accurate perception of the hazardous process, an awareness of the spatial extent of hazardous areas, an ability to recognize the conditions that are likely to generate landslides and debris flows, and the practical steps they can take to ensure their safety" (Schweig et al, 2010).

The design of this research study was predicated on contributing to the recommendations outlined by the USGS VDAP scientists. Some of the results of this research address parts of this stated need. The outcomes demonstrate the importance of incorporating all stakeholders in data gathering, processing, and dissemination. The tenets of the research and project design help equip local institutions and community leaders with the necessary information and tools to help in decision-making prior to and during emergencies, while fostering collaborative research and engagement. The participatory nature of the research explores an underused strategy to achieve risk reduction goals in the at-risk areas on volcanoes in underdeveloped countries. The goals of this study are as follows:

1. Improve the understanding of institutional efforts to help communities prepare for hazard events and evaluate how these efforts are perceived/adopted by area populations.
2. Improve the understanding of resettlement policy designs and implementations and the effects on populations' physical and social vulnerability.
3. Form an engaged and trained team of citizen scientists that can strengthen community-based slope and precipitation monitoring, establish baseline data to improve landslide forecasting models, and communicate hazard information effectively to the public and relevant institutions.

These goals were attained by focusing on four main project objectives:

1. Determine what strategies are currently being used by institutions in El Salvador to make advancements toward risk reduction and evaluate their effectiveness based on qualitative feedback and ethnographic data gathered from targeted populations and observations of the crisis management experience during the October 2011 Tropical Depression 12E emergency.
2. Determine the impact that resettlement policies had on affected residents' livelihoods, social networks, and aspects of social and physical vulnerability

through participant observation, semi-structured interviews, and document review.

3. Use a combination of precipitation monitoring and geophysical methods to help better characterize slope stability at San Vicente Volcano.
4. Integrate the results from characterization of slopes with institutional/community involvement in risk reduction efforts and outreach through participatory monitoring exercises and training programs led by the Universidad de El Salvador.

1.5 Dissertation Outline

The following three chapters detail the methods, results, and interpretations of: 1) how DRR efforts evolved in San Vicente after Hurricane Ida; 2) the complexities of relocating at-risk communities; and 3) geophysical research and outreach activities which strive to improve our understanding of hazard triggers at San Vicente volcano while educating decision-makers and the public alike. The focus is on the experiences of the 2009 Hurricane Ida and the 2011 Tropical Depression 12E disasters because these events spurred changes in the existing management system and provided valuable learning opportunities to evaluate strengths and weaknesses in disaster preparedness and management, establish a collaborative DRR working group, direct university research towards slope stability and debris-flow hazard assessment, and analyze the impacts of resettlement policies in a post-disaster context. Synopses of the following three chapters are provided below in an attempt to synthesize the results and interpretations culminating from this body of work.

1.5.1 Chapter 2: University Contributions to Risk Reduction following a Disaster: A Case Study of Reorienting Natural Hazards Research Efforts at San Vicente Volcano, El Salvador

Bowman et al. (in review) uses qualitative research methods like participant observation, semi-structured interviews, and document review to analyze the evolution of DRR in San Vicente. Faculty at the Universidad de El Salvador – Facultad

Multidisciplinaria Paracentral (UES-FMP), which is located in the city of San Vicente, experienced the tragedy firsthand and perceived that chaotic project implementation, redundant objectives among various groups, and poor coordination hindered the effectiveness of pre-event DRR efforts. This paper highlights how the UES-FMP became a leader in the San Vicente region to help strengthen collaborative networks between disaster risk reduction institutions through its formation of a 5-month-long disaster risk reduction training program. The UES-FMP also directs new research efforts to better characterize landslide triggers, land-use changes, the local watershed and flooding hazards, meteorological data, and specific factors contributing to vulnerability and risk. The UES-FMP continues to lead training programs toward reducing disaster risk and has established El Salvador's first ever Master's degree program in disaster risk management.

1.5.2 Chapter 3: Disaster risk reduction and resettlement efforts at San Vicente (Chichontepec) Volcano, El Salvador: toward understanding social and geophysical vulnerability

Bowman and Henquinet (2015) use ethnographic methods within the heavily damaged community of Verapaz to analyze local residents' perceptions of a relocation scheme and new monitoring strategies designed to reduce physical vulnerability to debris flows. Verapaz was completely destroyed in 2009, and the community quickly became the "poster community" of the Hurricane Ida debris flow disaster. This work builds on Bowman (2009) and Bowman and White (2012), which explored community perceptions of NGO-directed disaster mitigation efforts at Santa Ana volcano. This publication demonstrates that aspects of social vulnerability related to relocation were not adequately considered, as the majority of homes deemed "uninhabitable" continue to be occupied by residents. Residents who received a new home have developed unanticipated strategies to diversify livelihoods and reduce risk to disasters. New monitoring strategies include networks of rainfall gauges, weather stations, and communication hubs to more effectively disseminate near-real-time hazard conditions to authorities and the public. These efforts were more successful at involving and empowering at-risk residents within the multi-institutional strategy to reduce disaster risk. This case is a prime example illustrating the pitfalls and unintended consequences of top-down DRR project designs

that do not adequately consider livelihoods nor the importance of social networks, yet also highlights residents' adaptive strategies in light of unfavorable disaster reduction policy.

1.5.3 Chapter 4: Interpreting saturation changes as a potential factor in shallow, rainfall-induced landslides from time-lapse seismic refraction, San Vicente Volcano, El Salvador

Bowman et al. (2015) describes the results of time-lapse seismic refraction field work conducted on the northern slopes of San Vicente volcano in an effort to determine whether changing water table depths throughout fluctuating seasonal precipitation might have implications for slope stability and shallow landslide triggers. Data were acquired during two field campaigns in May and November 2013 marking the end of the dry season and end of the wet season, respectively. The results demonstrated survey repeatability and a validation of methods used, however saturated layers and perched water tables, which were hypothesized to be a contributing factor to rainfall-induced landslide generation, were not able to be imaged as seismic velocities throughout all imaged seismic refractors were similar in both campaigns.

1.6 Conclusions

Decades of different internationally accepted plans to reduce disaster risk have been put in place, but further refinement of strategies continues. Most recently, the UN Sendai Framework was ratified in March 2015. This resolution emphasizes that effective disaster risk reduction relies on coordination mechanisms with relevant stakeholders, including academia, at all levels to ensure mutual outreach, sustainable partnership, and complementarity in roles and accountability.

The Agricultural Sciences department at UES-FMP in San Vicente is one example that demonstrates the level of cooperation recommended within the new framework's design for effective DRR. Agricultural engineers at the UES-FMP served as mentors and partners throughout the research included in this dissertation. Since the 2009 disaster, the following aspects related to DRR in San Vicente have become clearer.

The UES-FMP shifted research and training activities towards DRR themes and has evolved as the region's unbiased partner to help coordinate and lead DRR efforts. Tropical Depression 12E in 2011 occurred during the UES-FMP emergency management certificate training program and provided real-life, hands-on experience for participants to engage in risk reduction efforts. This experience helped identify weaknesses to the existing communication protocol, which were remedied in the months following the emergency. The emergency also provided an opportunity to clarify DRR practitioners' roles and responsibilities during hazard events.

UES-FMP-led projects promote inclusion of State institutions at national and local levels and incorporate sectors proportionately affected by disasters, especially the rural poor. The results from ethnographic research conducted in Verapaz demonstrated that residents', sheltering, relocation, and residence behavior differed from institutions' desired outcomes because project designs did not sufficiently address residents' concerns related to aspects of social vulnerability like livelihoods, family networks, and proximity to agricultural lands. Results of the Verapaz study and ongoing UES-FMP projects highlight the importance of designing future projects with a full consideration of these elements, which brings social vulnerability into a broader regional discussion. Partnerships with national and international aid organizations, universities, and local governmental institutions are key to help sustain ongoing DRR training and certificate programs, as well as new areas of hazard research and monitoring. Five years of collaborative efforts to enhance San Vicente's ability to reduce disaster risk has resulted in El Salvador's first-ever certified Master's degree program in Disaster Risk Management at UES-FMP. This step represents a restructuring of the University by integrating disciplines to develop a new curriculum and program to meet the needs of the region. Through the academic program, new research and trained individuals will help further address risk issues throughout El Salvador.

An effort to better understand the relationship between seasonal precipitation and water table depth did not indicate that impermeable layers are present to create perched water tables that could trigger shallow landslides. Though data obtained did not image saturated layers, repeatability between surveys showed that the time-lapse seismic

refraction methods worked well in the volcanic terrain. Changing field campaign design might bolster future results if survey sites were reoccupied under different conditions, especially if campaigns could be performed soon after periods of heavy precipitation and combined with other geophysical methods like resistivity.

The region surrounding San Vicente volcano has a long history of natural catastrophes and is now receiving systematic attention towards hazard mitigation planning. Improving DRR for the region is an iterative process where the practitioners use data, observations, and experiences to identify areas to improve the current system and better prepare for future hazard events. Experiences from the San Vicente case can be applied to improve DRR and hazard research efforts in other areas.

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Chapter 2: University contributions to risk reduction following a disaster: A case study of reorienting natural hazards research efforts at San Vicente volcano, El Salvador

Abstract

Disaster risk reduction (DRR) efforts and research are lacking in many hazard-prone areas around the globe. Governmental initiatives in El Salvador recently sought to address challenges to disaster and emergency management that became evident following a series of disasters spanning 1998 to 2005. The region surrounding San Vicente volcano, El Salvador, has a long history of natural catastrophes and yet, until recently, has received little systematic attention towards hazard mitigation planning. The debris-flow disaster in November 2009, triggered by rains from Hurricane Ida, was the first time the country systems were needed, and an in-depth review of the evolution of these systems is the focus of this paper. Faculty at the Universidad de El Salvador – Facultad Multidisciplinaria Paracentral (UES-FMP), which is located in the city of San Vicente, experienced the tragedy firsthand and perceived that chaotic project implementation, redundant objectives among various groups, and poor coordination hindered the effectiveness of pre-event DRR efforts. Poor potential-hazard awareness, no warning and monitoring systems, and unclear crisis-response responsibilities all contributed to over 200 deaths in the region. Faculty group then led a comprehensive community effort to identify weaknesses and plan better for the next catastrophe. Their approach encompassed conceiving and implementing research, field, and training activities for improving hazard understanding and communication in order to better inform decision makers and the public. UES-FMP partnered with research and development groups to gather hydrometeorological data, model hazards, and train local stakeholders. UES-FMP encourages DRR practitioners to focus on interdisciplinary methods to help guide project design. Experiences from San Vicente can be applied to improve DRR and hazard research efforts in other areas.

Based on: Bowman, L., Gierke, J.S., Cruz Centeno, J.F., in review. University contributions to risk reduction in a post-disaster context: A case study of reorienting research efforts at San Vicente volcano, El Salvador. Geological Society of America Special Volume, *Geoscience for the Public Good*.

2.1. Introduction

Since the declaration of the International Decade of Natural Disaster Reduction (IDNDR) in the 1990s, many Latin American countries have tried to improve their ability to minimize the impacts of hazardous events. Corominas and Marti (2015) detail specific policy advancements in El Salvador, Nicaragua, Costa Rica, Mexico, and Chile over the last two decades to meet the disaster risk reduction goals proposed in both the IDNDR and the Hyogo Framework for Action. The higher frequency and greater impacts in higher population densities in El Salvador have led to further institutional and policy changes to better address systematic weaknesses that become apparent in the aftermath of a disaster.

El Salvador has 20 potentially active volcanoes, six of which have had significant eruptions in the last 125 years (Global Volcanism Program 2015). Though San Vicente volcano (known locally as Chichontepec: 13.5950° N, 88.8370° W) has had no historical eruptions, it is the site of at least seven debris-flow events (Major et al. 2004; Smith 2012; Barrera and Guevara 2008). Several recent major disasters in El Salvador have led to policy changes within the national government to reduce the risks to life and property from natural hazards. After Hurricane Mitch (1998), El Salvador experienced two deadly earthquakes in 2001 (M 7.7 on January 13 and M6.6 on February 13) causing heavy human (1,159 people killed) and economic losses ($1.2 billion US) (Marti and Jovel 2004; Wisner 2002; Jibson et al. 2004). The *Servicio Nacional de Estudios Territoriales* (SNET, National Service for Territorial Studies) was formed as a result in order to improve environmental monitoring and forecasting capabilities to better prepare for hazardous geological and hydrometeorological events. The crisis forecasting and warning capabilities of SNET were first tested in 2005 when Santa Ana volcano erupted (Volcanic Explosive Index of 3) on October 1 and Hurricane Stan on October 2. The rains caused flooding, landslides, and debris flows. Recognizing the need for more centralized crisis response, the government then formed *Protección Civil* (Civil Protection: CP, hereafter) to complement the forecasting and warning responsibilities of SNET. CP was charged with preparing communities for hazardous events, communicating hazard information

provided by SNET, declaring emergency alerts, and responding to communities in need following disasters.

The emergency systems and procedures developed by SNET and CP were not needed until the 2009 Hurricane Ida debris flow disaster at San Vicente volcano. Heavy rainfall from Hurricane Ida, starting in El Salvador on 7 November 2009 and increasing for two days, triggered landslides and debris flows on 8 November that killed more than 200 people and caused considerable damage to infrastructure in the five municipalities on the northern flank of the volcano. The DRR efforts fell short in many respects. No warnings and poor preparedness were evident throughout the unfolding of the disaster. Even alerts regarding the emergency were not issued until the morning after the event (Bowman and Henquinet 2015; Tellman 2011). Communities and institutions were not adequately prepared for responding in terms of communicating warnings and preparations for responding to events, coordinating evacuations, preparing emergency shelters, etc. (Bowman and Henquinet 2015).

After the 2009 disaster, many new and revised structural and organizational changes were promulgated nationally and locally to avoid similar shortcomings in the future. The disaster spurred a significant aid response from governmental and nongovernmental organizations (NGOs), university groups, and aid organizations first dedicated to immediate relief for victims and reconstruction and then directed toward disaster risk reduction (DRR) efforts. Since the Universidad de El Salvador – Facultad Multidisciplinaria Paracentral (UES-FMP) is located in the town of San Vicente and was frequently used as a resource for information and support from arriving aid institutions, it became evident to several faculty that many DRR institutions competed for resources and had redundant, overlapping objectives. Similarly, there was very little inter-institutional collaboration and little sharing of project objectives and results.

UES-FMP used a two-pronged approach to learn from the catastrophe and improve future disaster management cooperation by: 1) soliciting support from international research and development groups to improve effectiveness of DRR institutions, and 2) reorienting their university research to improve hazard understanding and communication in order to better inform decision makers. By partnering with

apolitical international research and development groups, UES-FMP plays an integral role in gathering hydrometeorological data, modeling hazard scenarios, training local students and technicians, and communicating results. To this end, UES-FMP contributes to DRR efforts by encouraging DRR practitioners from NGOs (e.g., Peace Corps, local and international university researchers, United Nations volunteers, Korea International Cooperation Agency, etc.) and governmental organizations (e.g., National Civilian Police, CP, municipal environmental technicians, etc.) to focus less on rapid project development/implementation and more on using background information to guide quality project design. Observations and recommendations from the San Vicente experience can be applied to improve DRR efforts in other areas.

This paper outlines the evolution of actions taken to identify and address the institutional weaknesses evident from the 2009 lahar disaster triggered by Hurricane Ida, and it provides a firsthand review of the effectiveness of the new systems and procedures during Tropical Depression 12E in October 2011. Unaddressed communication problems apparent after Hurricane Ida proved challenging again during Tropical Depression 12E, as well as the importance of establishing baseline data and more hazards-focused research. Continued commitment towards addressing these issues is needed, but the partnerships and collaborative efforts have led to important improvements in communication, coordination, and data gathering. What follows is a case study that highlights a suite of critical components for more effective DRR planning and management.

2.2 Background and Methods

El Salvador has had a long history of disasters as a result of its tropical latitude and precarious tectonic position adjacent to the convergent plate margin where the Cocos plate actively subducts beneath the Caribbean plate (Figure 2.1). Earthquakes, volcanic eruptions, landslides, tsunamis, floods and droughts are hazards faced by this small, densely populated developing nation. The potential frequency and severity of these hazards make citizens of El Salvador the eighth most vulnerable in the world according to the World Risk Report (Mucke et al. 2014).

The aforementioned series of recent disasters brought risk issues to the forefront of national discussion and policy. As a demonstration of its commitment to improve hazard forecasting and emergency management, the national government created SNET in 2001 so as to better monitor potentially hazardous geological and meteorological phenomena. In 2005, the Salvadoran Congress passed a law creating a new Civil Protection institution charged with communicating information generated by SNET, responding to communities affected by disasters, and preparing the population for future hazard events.

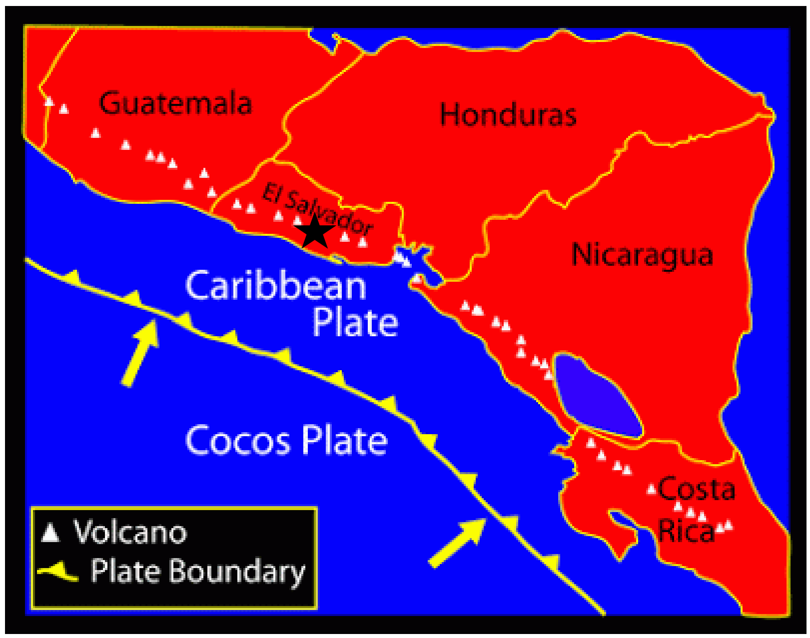

Figure 2.1 Plate Boundaries and Volcanic Front of El Salvador (Modified from Scripps Institution of Oceanography 2012). The location of San Vicente volcano is indicated with a black star.

After both of these new agencies operated for several years, the first major disaster occurred as a result of heavy rains from Hurricane Ida at the end of the rainy season in 2009 (Figure 2). In less than 36 hours, 7-9 November 2009, 450 mm (355 mm over a period of five hours) of rain fell on the already saturated slopes of San Vicente volcano, triggering shallow landslides (CEPAL 2010; Government of El Salvador 2009). These mass movements bulked and behaved as debris flows in the steeply incised channels on the northern flank of the volcano. Volumes of these flows (estimated to be more than 350,000 m^3) were greater than the channels could convey, thereby inundating

the less-steep, more-populated alluvial areas (Government of El Salvador 2009; Schweig et al. 2010). Debris flows of this magnitude had not occurred in the region since 1934, which was long enough ago that memories of the previous disaster had mostly faded and drainages slowly aggraded. Local residents, especially poorer families without access to fertile, safe land, had begun living on and farming these areas, mostly in the town of Verapaz (Bowman and Henquinet 2015). By 2009, entire neighborhoods, including churches and clinics, had been constructed on top of the 1934 lahar deposits. Though SNET had forecasted hurricane-level rain, CP's warning mechanism (color-coded warnings ranging in order of increasing severity: Green, Yellow, Orange, and Red) remained at Green (lowest level) and no warning or evacuation was issued. The magnitude of the event was completely unforeseen, catching both national and local governmental institutions by surprise. CP did not issue an Orange alert (which "mobilizes civil authorities, the armed forces and police and fire departments and all humanitarian agencies working in the affected regions to prepare for evacuations, equip places of refuge and maintain public order") until the morning after the disaster when it was too late for many of the victims (Tellman 2010; Fagen 2008: 11).

Figure 2.2 Hurricane Ida aftermath in the town of Verapaz. The first photo is taken downstream from the destroyed bridge over *Quebradona* Creek. The second photo shows damaged homes and debris flow deposits on a main road in Verapaz downstream from where the lahar left the *Quebradona* Creek channel. (Photo credit: Jose Fredy Cruz Centeno).

Five municipalities (Guadalupe, Verapaz, Tepetitán, San Cayetano/Istepeque, and San Vicente) were most heavily impacted by the debris flows (Figure 3). The southern portion of Verapaz and marginalized populations along the Acahuapa River banks in San Vicente city were completely destroyed, and entire neighborhoods were swept away or buried in debris. In total, official estimates of fatalities reached more than 200 individuals, and unofficial estimates were more than twice the official but went uncounted for they were never recovered (*Protección Civil* 2009). In addition to the homes and buildings that were destroyed, crops and infrastructure were also heavily damaged, totaling more than $314 million (El Salvador uses USA currency, so dollar figures herein are all in US dollars) in losses, which is more than 1.4% of the country's gross domestic product (Government of El Salvador 2009). Unfortunately, part of the lack of investment in DRR initiatives and proper preparedness plans can be attributed to poor management of relief funds, decentralization of state institutions, and even corruption (cf. Tellman (2011) for a complete review). For example, former El Salvadoran president Francisco Flores was recently indicted on corruption charges for misuse of $15 million of disaster aid between 1999 and 2004 after Hurricane Mitch and the two earthquakes in 2001 (Renteria 2014).

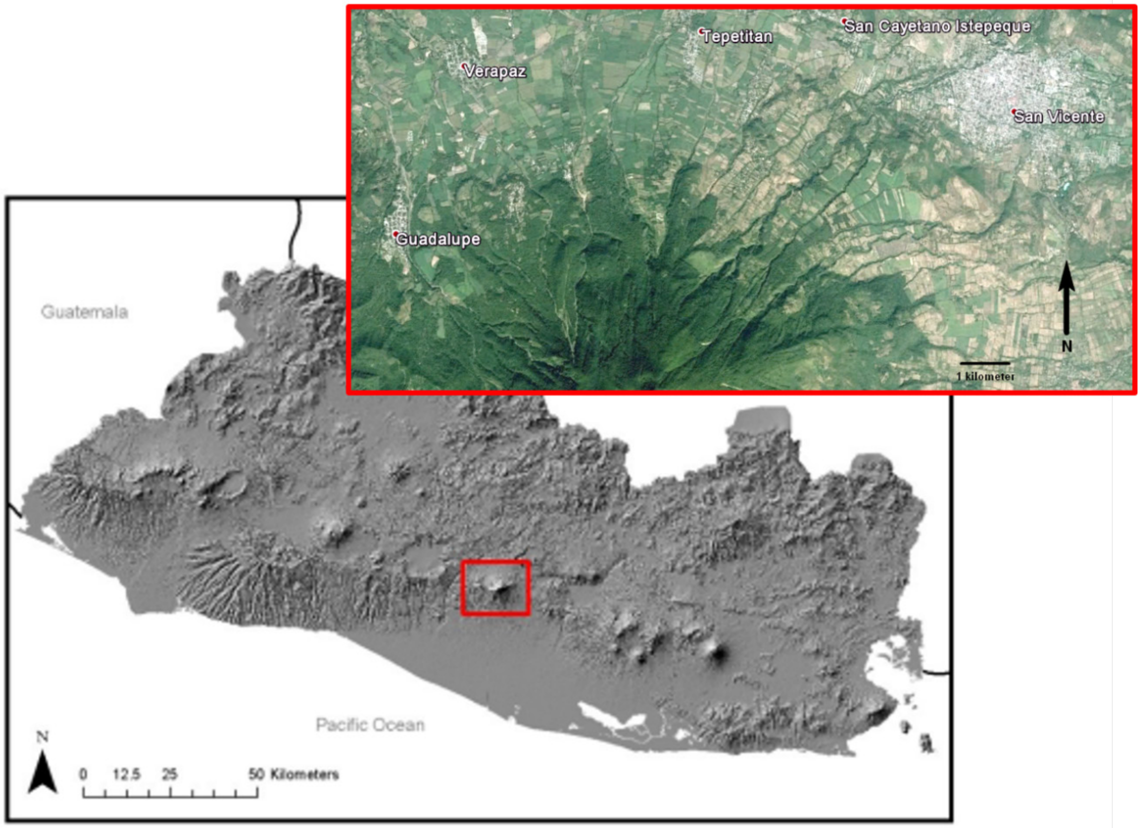

Figure 2.3 Map of El Salvador and inset of San Vicente volcano, encompassing 5 focus municipalities (Modified from Smith et al 2015).

In the aftermath of the 2009 lahar disaster, many governmental and nongovernmental organizations invested money in DRR efforts in the five aforementioned municipalities. International and national aid arrived within days and continued for weeks. Within two months, many short-medium term projects were underway. Agricultural engineers working for UES-FMP (Professor Fredy Cruz Centeno) and CEPRODE (Rutilio Antonio Parada Galan) remembered that the hasty arrival of aid led to project objectives that often overlapped and increased competition for resources and community support (Parada Galan, personal communication, May 30, 2012). Recognizing this organizational weakness, faculty from the Agricultural Sciences department of UES-FMP began soliciting international support from the U.S. Peace Corps Response and Korea International Cooperation (KOICA) volunteer programs.

The Geological and Mining Engineering and Sciences department at Michigan Technological University (Michigan Tech) began a Peace Corps Masters International (PCMI) program in Mitigation of Natural Hazards in 2004 (cf. Tubman et al. (this issue)). Three Michigan Tech PCMI students previously served in El Salvador, and one regular M.S. student spent five months on his thesis project related to disaster prevention and mitigation at Santa Ana volcano in early 2009, prior to the San Vicente lahar disaster. Bowman and White (2012) highlighted NGO challenges in a post-disaster context with affected residents who demonstrated community priorities that differed vastly from NGO objectives. Subsequently, this student, who is lead author of this work, began doctoral studies focusing on the November 2009 lahar disaster at San Vicente volcano. Previous field research provided the necessary background required to fulfil the needs requested by UES-FMP and Peace Corps Response—El Salvador at San Vicente volcano. The data and observations in this paper originate from research conducted with UES-FMP for a total 15-month-long field season. Agricultural engineers from the Agricultural Sciences department at UES-FMP originally defined project and research objectives around: 1) strengthening institutional collaboration; 2) identifying community leaders and local stakeholders; 3) designing formal emergency management training activities for residents and institutional representatives; 4) advising UES-FMP students in DRR-based thesis projects; and 5) identifying research priorities regarding natural hazards threatening the population around San Vicente volcano.

Concomitantly, Peace Corps—El Salvador created a new, one-of-a-kind volunteer program titled Disaster Prevention and Mitigation (DPM) and invited two additional Michigan Tech PCMI students to help train and prepare communities to reduce disaster risk. The development of a new Peace Corps program that recruits and trains DPM volunteers further demonstrates the development sector's need to incorporate grassroots DRR efforts in rural communities throughout El Salvador.

The data collected for this analysis was obtained through several ethnographic tools. Participant observation was carried out during a 15-month-long field season where observations were made during community meetings, field trips, certificate program courses, and the management of the Tropical Depression 12E emergency. Semi-

structured interviews of 11 DRR practitioners involved in the post-Ida recovery and management of Tropical Depression 12E emergency from both NGO and GO sectors were conducted, transcribed, and coded using Atlas.ti qualitative data processing software in order to identify recurring themes regarding disaster management and the evolution of disaster risk reduction in the San Vicente region. Detailed field notes were taken to help triangulate data from what was observed in the participant observation and the information and ideas gathered in interviews. Finally, additional information was gathered through document review from NGO and GO project publications and the media.

2.3. Results

UES-FMP Agricultural Sciences faculty provided their expertise to the GO and NGO DRR institutions arriving and working in San Vicente. As self-appointed, apolitical liaisons for a variety of new projects, Agricultural Engineer and UES-FMP professor, Fredy Cruz Centeno (co-author of this work), mentored PCR and KOICA volunteers to help coordinate and restructure the implementation of institutional efforts18 months after the Hurricane Ida disaster (April 2011). The following reflections and results of the ethnographic data chronologically detail the steps taken with regard to stakeholder and community leader identification, training of local emergency managers and volcano observers, active participation in a real-life emergency management scenario, and the evolution of research activities. Initially, all stakeholder priorities revolved around addressing the lack of preparedness experienced in 2009. Greater interest was given to geologic field research after the Tropical Depression 12E emergency in October 2011. The results also describe the growing network of external support that aided both institutional coordination and the geohydrological research efforts that broaden the understanding of hazards and vulnerability.

UES-FMP and the San Vicente Civil Protection brigade organized a multi-institutional meeting in May 2011 to review the recently revised plan titled (*Plan Invernal*), "Rainy Season Plan." Government and CP representatives from each of the five heavily-damaged municipalities, as well as individuals from the Red Cross, CARE

international, Habitat for Humanity, *Centro de Protección para Desastres* (CEPRODE, Center for Disaster Protection), the *Fundación de Desarrollo* (FUNDE, Foundation for Development), and local police and fire departments. This gathering was used by UES-FMP to present itself as a resource to be used by regional practitioners and explain its plan to develop a five-month *diplomado* Certificate program for combined classroom and field courses focused on hazard assessment, risk reduction, and emergency management and response. Public response to this idea was overwhelming, and FUNDE and CEPRODE acquired additional resources for the development of this course over the following three months.

In August 2011, 54 participants began the diploma program. Enrollment was capped to accommodate the physical space available for the courses and to facilitate the field activities. Students consisted of UES-FMP recent graduates, community leaders from all five municipalities, CP technicians, NGO representatives, National Civilian Police and Fire Department officers, Peace Corps trainers, Brazilian technicians from a United Nations Development Program project, and municipal employees from Natural Resource and Environment sectors. Coursework and trainings held by experts and certified emergency management trainers made up the majority of the first three months. These lessons included curricula and certifications approved by USAID regarding: Management of Centers for Emergency Operations (MACOE); Evaluation of Damages and Needs (EDAN); management of shelters; aid distribution; and Early Warning Systems (EWS). A crisis simulation exercise was planned to conclude this portion of the program in order for each student to practice a role and assume a responsibility while managing a hypothetical crisis. This simulation was never performed because Tropical Depression 12E arrived and provided an opportunity to put into practice what had been learned. Classes for the program were suspended during the emergency but resumed through December 2011.

2.3.1 Tropical Depression 12E

On 10 October 2011 Tropical Depression 12E entered El Salvador causing nearly continuous rainfall for 12 days and produced rainfall accumulations that equaled the

devastating amounts from Hurricane Mitch in 1988 (International Federation of Red Cross and Red Crescent Societies 2011). Many areas reported rainfall accumulations surpassing annual rainfall averages—up to 1400 mm of precipitation. During this emergency, CP established *Centros de Operaciones de Emergencias* (COEs) in municipalities throughout the country. COEs are standard CP protocol and are the mechanisms by which CP coordinates and controls all operations during emergencies, which facilitates "an efficient response to any incident and allows inter-institutional resources to be used in an efficient manner" (Ministerio de Gobernación y Desarrollo Territorial 2012). By October 18, CP reported 32 deaths due to landslides and flooding throughout El Salvador. In San Vicente and the surrounding municipalities, this was the first time that newly trained individuals assumed the responsibility of managing a real emergency in the COEs.

Since a simulation could not be performed prior to the arrival of TD12E, the first three days of COE management proved chaotic because of poor or delayed communication, confusion about individual roles and responsibilities, and general inexperience of managers. My (LB) own observations regarding this experience were gathered from my participation in the emergency management and follow-up interviews with participating DRR practitioners. This example, translated from a Spanish-language interview, reflects the confusion and challenges activating the proper COE protocol during the first days of the emergency:

> *We had just finished the "Center for Emergency Operations Management" training program. Students had the tools, but they didn't feel self-assured. I had to get involved because they were not well-organized. Our NGO is not geared for actual response—we are trainers and facilitators. Our role is to assess our program, and we recommended that the action plan had to change, so we recommended to the mayor and police chief to activate the COE protocol. The management team chose a leader and divided responsibilities. At this point, they* [the students/team members] *put their training into practice and they realized that this methodology works—what you need to have is confidence that the management plan can be executed, and that was demonstrated that day and throughout the rest of the emergency. That was one of the biggest successes of our project, because training, training, and more training is one thing, but to put that knowledge to the test during an emergency is the true goal.* NGO Technician

Early in the crisis, CEPRODE took an active role in reminding managers of their training and responsibilities which helped establish a coherent framework for communication as well as a hierarchy of management—all concepts that were part of the Diploma program. One CEPRODE technician summed up their role in the COE by saying:

> *Our role during the crisis* [Tropical Depression 12E] *was to unite a variety of institutions with the University of El Salvador…and provide logistical and assessment support when the COEs were established. This case was interesting because we had just finished our training in how to manage Centers for Emergency Operations, but we had not yet had a simulation exercise to test the students' knowledge, and we had not provided the training about shelters and evacuations. So this gave us the opportunity to put into practice the knowledge and training that we had provided. Our donors* [USAID and Lutheran World Relief] *were very content that participants were able to be involved with a real-life emergency.* NGO Technician

After this mid-emergency intervention, operations ran more smoothly. Shelters were constructed, at-risk families were evacuated, food and other aid were effectively distributed, and hourly precipitation data were reported from local observers and municipal weather stations to the CP authorities helping to manage the COEs. The duration of the yellow and orange alert status (11 days) required that COE managers work in 12-hour shifts, resulting in ample experience for each of the Diploma students involved. The event provided a perfect platform for the students to put into practice the theoretical management skills learned in the training program, as well as identify weaknesses that could be improved upon during future emergencies.

After the emergency concluded, and the diploma course resumed normal programming, students that took part in the emergency management, lecturers, and field-trip leaders referred to the Tropical Depression 12E experience and focused on addressing some of the structural weaknesses that were discovered. For example, CEPRODE worked alongside CP to improve the communication network. One CEPRODE employee recalls the communication challenges during the TD12E management and the importance of integrating the network with CP:

> *The first thing we realized is that our communication system* [local observers to Civil Protection] *failed. We had to insist before the National Commission that*

> *they approve the same frequencies* [for local observers] *as the frequencies used by Civil Protection. During the emergency, they had to use cell phones* [instead of radios] *but few people have money for that. If users don't have minutes on their* [prepaid] *phone, the system failed. Our project could supply minutes to the users, but what happens when our project is over? The whole communication system breaks down. We addressed that weakness by coordinating with Civil Protection and getting the* [two-way] *radio frequencies approved for the communication network.* CEPRODE Employee

Though TD12E induced problematic flooding in parts of San Vicente, the storm triggered only small landslides primarily at road cuts. At the end of the crisis, there were no casualties in the focus area. The magnitude of the event cannot be compared to the crisis experienced during Hurricane Ida in 2009; however, the effectiveness of the network of local observers, increased awareness of the public, improved preparedness by local residents, and efficiencies of the managing institutions were apparent. Weaknesses in the system were identified, which provided an opportunity for further improvements.

2.3.1.1 Local Observers

An especially important outcome of this event was the receipt of reports from recently trained local observers strategically located on the upper flanks of San Vicente. CEPRODE and CP efforts to incorporate local residents into a precipitation and slope monitoring network proved extremely beneficial. At least seven surface cracks had formed (or became apparent) during the storm. These cracks tended to occur along the tops of ridges or along contours on the upslope regions of agricultural fields and coffee plantations. All of their orientations suggested the potential for onset of mass movements. Local observers used two-way radios (provided by CEPRODE) to report the phenomena to CP authorities. CP sought assistance from UES-FMP and CEPRODE, so a field campaign was organized with some of the Diploma students to measure horizontal and vertical displacement of the cracks, as well as to georeference each location. One month later, UES-FMP faculty and collaborators organized a geophysical field campaign using seismic refraction and resistivity methods in an attempt to characterize bedrock and water table depths in areas where surface water runoff infiltrated surficial cracks that appeared during Tropical Depression 12E. These cracks were suspected as places for potential

slope failure and of particular concern to the local observers who discovered them. Seven such areas were visited, georeferenced, and measured. The geophysical surveys were conducted only once and thus were inconclusive, but the group activity did contribute to strengthening interagency cooperation through the opportunity to work on the issue in a hands-on fashion, while providing benchmark data for future monitoring of slope movement.

2.3.1.2 Weather Station Network

Rainfall intensity and accumulation data from local observers helped CP and the COEs. CEPRODE secured funding from the United States Agency for International Development (USAID) to install a Davis Vantage Vue weather station at each of the five municipal government buildings where the COEs are established during emergencies. An additional weather station was installed at UES-FMP campus. At times when the system has been fully operational, this monitoring advancement provided real time precipitation data, further strengthening CP's ability to warn communities in a timely manner. Even when the real-time internet uploading service is down, local observers can report data directly observed from their respective station to CP and COE managers.

Michigan Tech provided server space in 2013 to UES-FMP and CEPRODE in order to create an online platform to host all meteorological data. The system has been wrought with problems, mostly due to internet security reasons. Michigan Tech and UES-FMP Information Technology personnel continue towards solving the problems so that the public will have continuous access to real-time and historic meteorological data. In the meantime, each municipality's COE has access to the weather station data for reporting purposes during emergencies.

2.3.2 Post 12E Efforts

Tropical Depression 12E demonstrated the importance of inter-institutional communication and data sharing, which further strengthened support for the UES-FMP goal to improve DRR collaborations. The positive momentum initiated with the Diploma program and annealed by the TD12E crisis continued following the management of

TD12E and was used during the following dry season to address the weaknesses identified during TD12E, as well as prioritize research efforts and solicit additional resources and support for continued efforts. Besides improved communication between local observers, municipality COEs, and CP for reporting rainfall and hazard conditions via the two-radio system, new research projects ensued to better understand slope stability and encourage citizen involvement with field campaigns.

Given the evident landslide hazard and the flooding that had occurred during TD12E, UES-FMP developed a proposal for the National Science Foundation (NSF)/United States Agency for International Development (USAID) Partnerships for Enhanced Engagement in Research (PEER) program. By partnering with Michigan Tech, UES-FMP was eligible to apply for research funding that was in support of the development goals of USAID. Their proposal, titled "Demonstrating the integration of ground-based monitoring and satellite remote sensing for forecasting landslides and flooding hazards in volcanic terrains," was funded in April 2012 and provided funding for field and distance learning equipment and travel for a remote sensing and hazard modeling workshop at Michigan Tech.

Additionally, scientists from the US Geological Survey (USGS) and SNET organized a hazard modelling workshop in January 2012, which provided tools and fostered skills for practitioners in San Vicente to develop locally-appropriate hazard maps for targeted, at-risk communities. CEPRODE, with assistance from UES-FMP faculty and Michigan Tech, developed five municipality-scale multi-hazard maps to serve as guides during DRR effort implementation and to assist decision makers during crises (Figure 4). Shortly after, in May 2012, a student from Michigan Tech conducted fieldwork at the 2009 landslide initiation points on San Vicente volcano to model the susceptibility of slope failure due to intense rainfall. The results from this study suggested that shallow water tables were a contributing factor to rainfall-induced landslides (Smith et al. 2015). Practically no information exists as to the depths to the groundwater table and bedrock on San Vicente volcano, so geophysical surveys were performed to examine the potential that bedrock is shallow and shallow perched aquifers could form during rainy seasons (Bowman et al., in preparation).

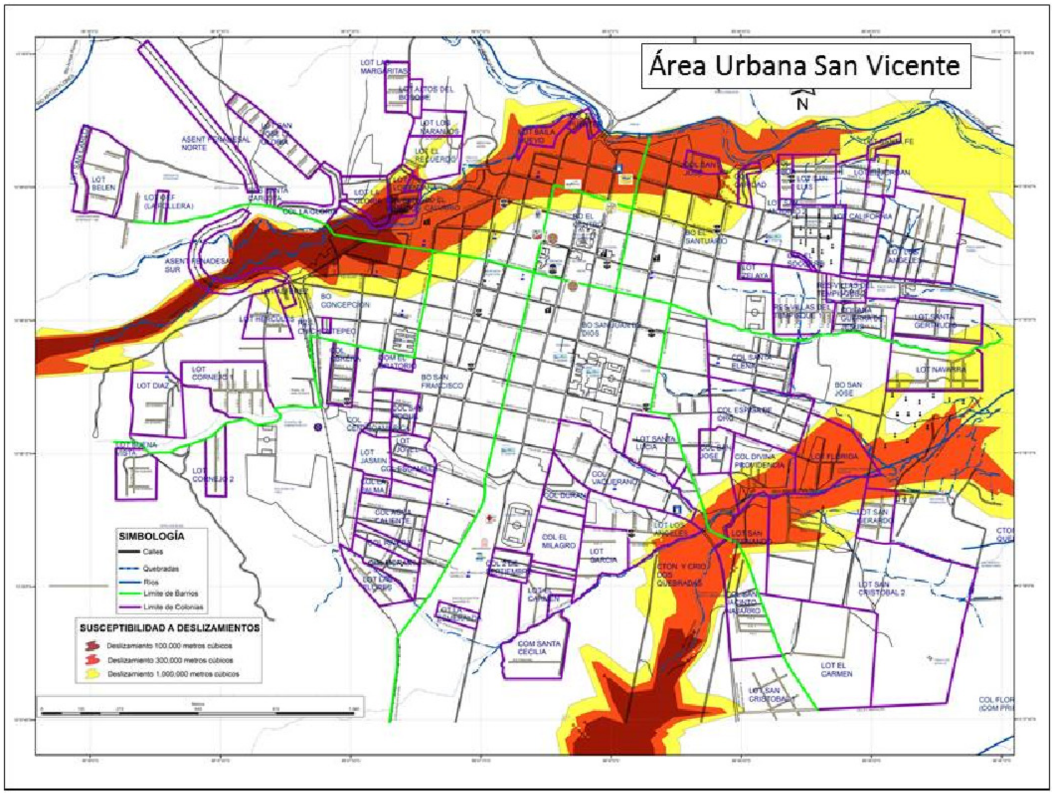

Figure 2.4 Example hazard map for San Vicente Municipality's urban area showing streets, creeks, rivers, and neighborhood boundaries with debris flow (of hypothetical volumes) inundation zones overlapping the base map.

The Smith et al. (2015) results led to an effort by Michigan Tech and UES-FMP researchers to use geophysical methods to monitor water table depths at three locations nearest to the 2009 slope failures. A host of local institutions conducted two field campaigns in May and November 2013—months marking the end of the dry season and end of rainy season, respectively. Seismic refraction surveys were successful at identifying stratigraphic layers; however, 2013 and 2012 proved to be a relatively dry years, so though the methods worked and the results show distinct layers, it was impossible to distinguish water table depth or depths of perched aquifers (Bowman et al., in preparation).

In March 2013, PEER-related activities began with the installation of Solinst leveloggers in five hand-dug wells located across the central portion of the Acahuapa River watershed. Pumping tests were conducted to measure hydraulic conductivities of the shallow aquifers. Additional PEER research was paired with geophysical field

campaigns in 2013. The network of monitored wells was coupled with two additional leveloggers installed within the upper and lower portions of the Acahuapa River to serve as stream gages to monitor seasonal changes in streamflow. This data, combined with meteorological data provided by the weather station network, will be used to create a water budget and model hydrologic conditions of the northern flank of San Vicente volcano to improve flooding hazard models and forecasts.

Research activities continued through 2013 with three additional visits to UES-FMP by Michigan Tech faculty and students, including currently serving PCMI volunteers. Furthermore, a UES-FMP Agricultural Sciences professor (FC) visited Michigan Tech for a customized remote sensing/hazard modeling workshop. Table 1 provides a synthesis of how DRR-related activities have evolved in El Salvador from 1998 through present day. Three years of collaboration after Hurricane Ida has resulted in a newly trained and tested group of emergency management practitioners, in-place weather and hydrological monitoring equipment, a classroom equipped with new computers, ArcGIS licenses and plotter, as well as video-conferencing equipment to continue distance learning initiatives between UES-FMP and Michigan Tech.

Table 2.1 Status Summary of El Salvadoran DRR Systems. (T = Tested; R = Restructured; E = Evolving; I = Initiated)

DRR System/Activity Description	Event Spurring DRR System/Activity/Evolution								
	Hurricane Mitch 1998	M 7.7 & 6.6 Earthquakes 2001	2005 Santa Ana Eruption and Hurricane Stan	Analysis of Systems in Place for 2005 Santa Ana Lahar	2009 Hurricane Ida Triggered Lahars	UES-FMP, Michigan Tech, CEPRODE, Peace Corps, KOICA Partnerships	2011 Tropical Depression 12E	2012 Post 12E Efforts (USGS, SNET, UES-FMP, Michigan Tech)	PEER/PIRE (UES-FMP & Michigan Tech)
Center for Geotechnical Research	Tested (T)	T, Restructured (R)[1]							
Servico Nacional de Estudios Territoriales (SNET)		Initiated (I)	T, Evolving (E)	n/a	T, E, Restructured (R)	n/a	T, E		E
Proteccion Civil (Civil Protection)			I	n/a	T, R	E	T, E		E
Municipal Civil Protection Brigades and NGO DRR Efforts			I	E[2]	E	E	E	E[3]	E
GPS Volcano Deformation Monitoring				I[4]				R[5]	E[5]
Risk Reduction Diploma Program						I	T, E		E
Centers for Emergency Operations (COE) Formation						I	T, R		E
Vulnerability Analysis and Population Relocation Study[6]						I	E		
MOU Development and Institutional Coordination						I	R, E	R, E	R, E[7]
Hazard Modeling and Remote Sensing Skill Development						I	E	E	E
Weather Station Network							I	E	E
Collaborative Modeling and Field Characterization of Landslide Susceptibility[8]								I	E
Watershed Monitoring & Hydrological Modeling									I[9]

[1]Several government organizations were reorganized under the Ministry of Environment and Natural Resources
[2]Bowman and White (2012)
[3]Civil Protection and Salvadoran NGOs continue to collaborate through trainings and field courses
[4]Lechner et al (2013)
[5]Santa Ana volcano GPS network was reoccupied; San Miguel volcano GPS network established for first time
[6]Bowman and Henquinet (in review)
[7]Cruz, J.F. et al (2013)
[8]Smith et al. (2014); USGS/SNET LaharZ workshop; Surface crack monitoring; Seismic refraction campaigns; Training at Michigan Tech
[9]Cruz, J.F. et al (2013)

2.4 Discussion

The unbiased position that UES-FMP holds among the stakeholder groups provided an effective opportunity in San Vicente to serve an important role in reorganizing and implementing DRR efforts and fostering collaborative relationships among the institutions working in the region. Municipal government environmental commissions are important partners in regional DRR projects and crisis management in El Salvador; however, the five municipalities do not all share the same political affiliations. The departmental capital, San Vicente, is governed by a mayor from one political party while the smaller, neighboring municipalities on the northern flank of the volcano are governed by opposing political parties. The recent history of civil conflict makes navigating the political differences challenging. Even NGOs working alongside government offices in one municipality can face challenges when attempting to expand their target areas if they are associated as supportive of one political party over another. For this reason, UES-FMP was integral by ensuring that representatives from each municipal government and organization were involved in training programs, field campaigns, and policy-making meetings.

A common occurrence in many post-disaster areas is that aid is initially abundant in the months after a disaster but often quickly runs out as "media coverage wanes and international attention turns elsewhere" while other priorities emerge and compete for limited resources (Inderfuth et al. 2005: 4). In San Vicente, financial investment and resources dedicated specifically to DRR were practically exhausted by August 2012. The 18-month CEPRODE project came to an end in August 2012. KOICA and Peace Corps Response/Fulbright volunteers/students departed in June and July 2012. A Brazilian team of United Nations Development Program volunteers focusing on hazard education in primary schools departed in May 2012. Funding through a Michigan Tech-acquired, NSF-funded project (Partnerships for International Research and Education: PIRE) and PEER-related efforts carried on throughout the end of 2013 when both projects concluded. Projects and funding have finite durations, which emphasizes the importance of establishing a functioning, sustainable framework so that local institutions will

continue after external support ends. This reality was apparent to UES-FMP, spurring them to emplace measures to foster longer-term collaboration.

In November 2011, UES-FMP and Michigan Tech signed a Memorandum of Understanding (MOU) that outlined ways in which both institutions would support each other throughout the implementation of the funded PEER research initiative. This formal document was not necessary from Michigan Tech's perspective, but the official MOU lends credibility to UES-FMP counterparts and facilitates continued efforts within their institution's administration. This document was upgraded in July 2012 to a more formal agreement that allows for both institutions to work beyond the scope of the previous research with the aim of continuing collaboration in areas of mutual interest after expiration of the PEER project. Similarly, UES-FMP established MOUs with CEPRODE and CP in order for all institutions to more easily access data collected and project results, as well as to facilitate ongoing trainings in the San Vicente area. These efforts continue today.

Their leadership role prior to and after the disaster strengthened the ability of UES-FMP to secure support from other development institutions working in the region. As funding and interest for continued DRR measures diminished, UES-FMP sustained the collaborative momentum by developing new partnerships with sustainable development objectives. UES-FMP created a MOU with The Foundation for Local Development (*Fundación de Desarrollo Local*) in order to develop an additional Diploma program called, "Management of Local Economic Development," which is directed at municipal representatives, food/agriculture cooperatives, and organizations fomenting ecotourism.

UES-FMP established another MOU with the national government's Ministry of Housing (*Ministerio de Hacienda*) regarding a funded initiative called, "Project to Strengthen Local Governments." Two additional diploma short courses will be offered in 2015 as a result of this new collaboration--one titled, "Disaster Risk Management and Municipal Development," and the other titled, "Economic Development and Sustainable Management of the Territory." These two courses are aimed at representatives from municipal environmental sectors, CP technicians, and municipal offices of economic

development to help strengthen emergency response and improve strategic urban development plans.

Local institutions continue developing an information database for the larger Jiboa River Valley, of which the Acahuapa watershed (and San Vicente) is part, using an ArcGIS platform to capture, process, and store relevant spatial and temporal data to improve municipal governments' access to information. The tool will be especially useful to identify vulnerable communities during emergencies and distribute resources more efficiently. Finally, UES-FMP and FUNDE support a grassroots youth development group and offer a special short course diploma program called, "Youths Transforming Their Territory." Each of the aforementioned diploma programs makes use of the newly equipped computer laboratory made possible by PEER and KOICA funding.

Formal agreements are an important product for academic institutions and practitioners in developing countries as they solidify partnerships and collaboration. They affirm longer-term commitments and challenge existing stereotypes that well-funded, visiting scientists focus solely on personal research goals without further consideration of broader needs from developing country host institutions (Barrett 2010).

2.5 Conclusions

Formal inter-institutional cooperation between national and international organizations, local governments, and universities improves the capacity for collaborative groups to undertake complex risk issues by providing the knowledge, tools, finances, and human resources to better address these problems. In San Vicente, inclusion of a wide variety of stakeholders nourished a collaborative environment where participants could voice ideas, express priorities, and posit solutions.

Involvement in diploma programs, field campaigns, and project planning meetings were inclusive in order to incorporate a range of participants from different backgrounds. This strategy is quite intentional given that "continued political polarity today reduces capacity in disaster response in El Salvador, as coordinating aid across governance scales (local-municipal-national) complicates distribution and decision-making" (Boyce 1995 *from* Tellman 2011: 37).

> *Although theoretically a national 'system' in the sense of cooperation among numerous institutions and levels of government, COEN has remained centralized—and in the view of opposition political parties, many municipal mayors and much of civil society—a closed 'club' used for distributing relief aid among supporters of the ruling party.* (Wisner 2001: 257)

Even UES-FMP administrators change frequently, and research priorities and budgets can quickly shift away from the current DRR advancements. Incorporating participants from a variety of institutions should ensure continuity and sustainability of ongoing efforts during periods of personnel turnover.

Similarly, integrating a variety of actors promotes continued involvement and support from their respective institutions. Diversity within the research and development groups allows institutions to share the burdens necessary to sustain efforts. Data collection, equipment maintenance, and continued research requires both human and financial investment. At San Vicente, these costs remain manageable as a host of institutions share responsibility for the costs related to transportation, technicians' time in the field, and upkeep of equipment.

Finally, though advancements in monitoring, data collection, and training in San Vicente have been achieved, there remain challenges to sustaining these efforts. Through the PIRE and PEER programs there were ample opportunities for face-to-face interaction between Michigan Tech and Salvadoran counterparts. Even though the PEER project helped equip a virtual learning classroom, online training sessions are sparse, and communication between institutions has lessened. Without site-specific field excursions planned for the near future, there is a risk that more time-dependent priorities take the place of project follow-up communication. Addressing this challenge requires improved planning by both academic institutions and a dedication to semi-frequent communication in order to continue to make research progress.

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Chapter 3: Disaster risk reduction and resettlement efforts at San Vicente (Chichontepec) Volcano, El Salvador: toward understanding social and geophysical vulnerability

Abstract

Despite a long history of volcanic debris flows on the northern flank of San Vicente Volcano, El Salvador, authorities and communities were ill-prepared for the lahars that occurred on Nov. 7-8, 2009. More than 250 people were killed by lahars resulting from shallow landslides, not to mention millions of dollars (US) in damage to houses, agriculture, and infrastructure. After the disaster, significant aid was invested in the region to reduce risk to future disasters. This case study uses the ethnographic tools of qualitative interviews, participant observation, and review of institutional documents to analyze two particular aspects of disaster risk reduction strategies in the town of Verapaz: 1) relocation of at-risk residents led by the Ministry of Housing and Urban Development, and 2) hazard monitoring and emergency management training programs led by Civil Protection, the University of El Salvador, and NGOs. The relocation effort, while effective at reducing physical vulnerability to debris flows, failed to incorporate livelihood, social networks, and cultural ties to homes in their project design and implementation. Since diverse livelihoods are keys to survival, and tightly-knit social networks help families share responsibilities and withstand shocks during hardships, many families returned to the high-risk area or opted not to relocate. Others have adapted using unanticipated strategies to benefit from the resettlement effort. On the other hand, the emergency management training and education programs valued local input, knowledge, and action, which has helped increase awareness and improved the overall capacity to manage emergencies through wide, local participation. The different approaches used in the two risk reduction initiatives reveal important lessons regarding the importance of community participation and creating accountable partners. Challenges derive from narrow understandings of vulnerability on the part of disaster risk reduction experts, who neglected to consider and understand kin networks and residence patterns that help maintain diverse livelihoods, as well as ensure safety and security. As demonstrated in the 2011 Tropical Depression 12E, effective public engagement and empowerment helped bridge the knowledge, awareness, and preparedness gaps that existed prior to the 2009 disaster.

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3.1 Introduction

Strategies for disaster risk reduction (DRR) in the aftermath of hazard events have evolved over the last decade. The "Hyogo Framework for Action 2005 – 2015" sponsored by United Nations International Strategy for Disaster Reduction (UNISDR) emphasized sustainable development and disaster prevention rather than reactionary responses (i.e., search and rescue and provisional sheltering) to catastrophic events (United Nations 2007). Many countries, including El Salvador, are adapting their risk reduction strategies around a plan of prevention; however, when disasters *do* occur, especially in developing countries, governmental and non-governmental relief and development institutions continue to consider relocation policies as viable, go-to strategies to remove people from geographically hazardous areas. These strategies narrowly focus on natural hazard vulnerability, while giving little thought to other types of vulnerability. The case of the response to the 2009 San Vicente, El Salvador disaster illustrates this point, while also showing ways in which natural hazard monitoring and communication improvements have been made.

In November 2009, heavy rains at San Vicente volcano in Central El Salvador (Figure 3.1) triggered shallow landslides that formed lahars. The debris flows affected several communities on the northern flank of the volcano, including Verapaz, triggering a massive relief and recovery effort. Nationally, disaster losses totaled approximately $240 million (USD), which represents more than 1.1% of GDP (United Nations 2010). Within the housing sector alone, more than 20,000 homes were either destroyed, badly damaged, or declared to be at-risk (United Nations 2010). Five months after the event, a $3.8 million (US) plan to relocate the most at-risk neighborhoods in Verapaz was underway (Ministerio de Relaciones Exteriores de El Salvador 2012). This research examines the ways in which at-risk populations in the small town of Verapaz were involved in mitigation programs and assesses the outcomes of these programs. Results demonstrate that despite best efforts, a significant gap persists between the authorities' perception of program success and the experience of the at-risk population near San Vicente. In particular, we examine this gap in the implementation of the resettlement project, and we

contrast this with more successful DRR initiatives that involved local residents in hazard monitoring strategies and communication. The 2009 debris flow disaster resulted in traumatic experiences for rural Salvadorans and underscored the challenges in implementing effective risk reduction when livelihoods and social support networks are disrupted.

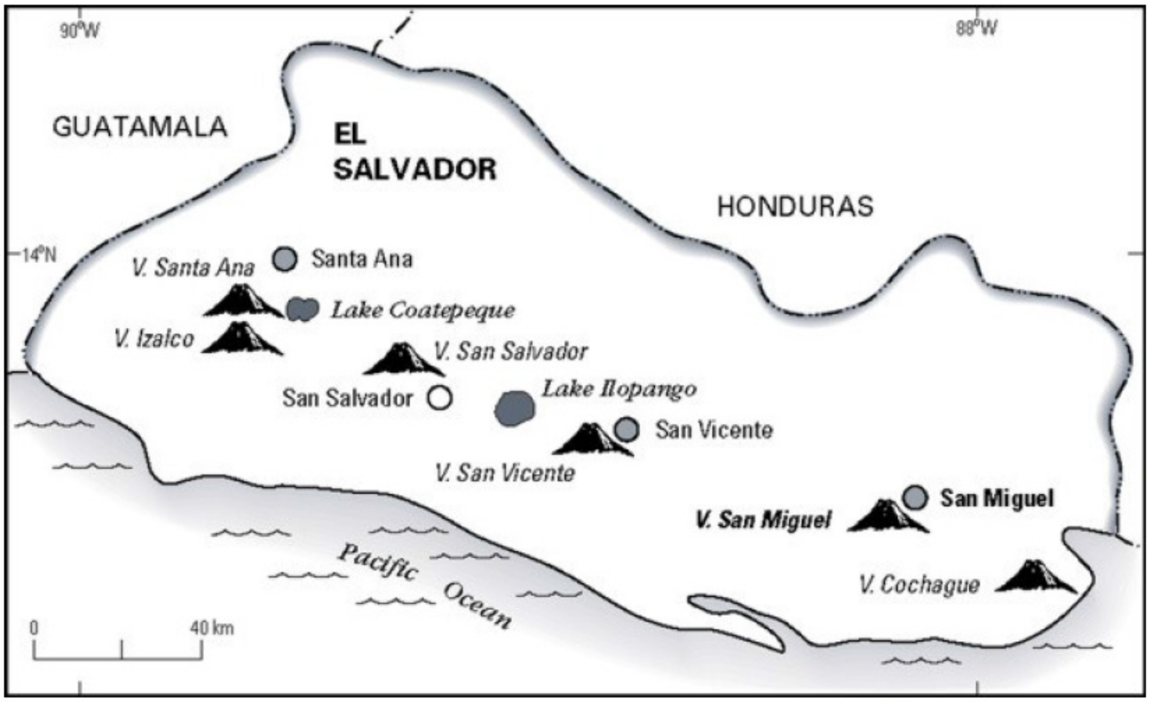

Figure 3.1 Location of El Salvador and principal volcanoes (including San Vicente Volcano). Reprinted with permission from Major et al. (2004).

Despite these shortcomings, new and sometimes unplanned livelihood and disaster preparedness strategies slowly emerged as families adapted to new settlement patterns after 2009. A long history of repression and the imposition of unfavorable settlement policies have stifled poor Salvadorans' social mobility, but also fostered creative ways in the disaster's aftermath for some to benefit from post-event relocation. Affected residents largely fall into four distinct groups: 1) those who lost everything and relocated to New Verapaz; 2) those who attempted relocating but returned to their original homes; 3) those who used the relocation project to claim an additional home to expand livelihood activities, and; 4) those who remain in risky areas of Verapaz and have

no intention of relocating to New Verapaz. The relocation effort had mixed results; some thrived while others struggled in the new settlement and opted to return to their old homes.

We first situate this study within the existing literature on relocation programs and place Salvadorans' vulnerability within the context of the country's colonial and political history. We next describe ethnographic methods and data analysis techniques employed throughout this study. In the results and discussion, we analyze the outcomes of uneven integration of the concerns and values of at-risk populations into the resettlement project planning and disaster risk monitoring efforts. In both cases, DRR experts focus on reducing vulnerability to natural hazards rather than incorporating a broader understanding of risk and vulnerability in people's lives in Verapaz. The natural hazard reduction focus was more effective in programs that incorporated communities in ongoing hazard monitoring and communication than in the case of resettlement. This case study illustrates a resettlement program that failed to view the process holistically and incorporate affected residents' concerns. It also highlights the advantages of engaging stakeholders in the scientific and decision-making/risk communication process. We found that resettlement was a more complex issue to plan for and successfully implement than improving communication and promoting local monitoring of natural hazards.

3.2 Background

3.2.1 Relocation of At-risk Communities and Disasters

Relocation is a complex issue, often resulting in hardships to those affected and in unanticipated outcomes. There is an extensive body of literature describing the challenges and pitfalls of post-disaster relocation projects (Johnson 2007; Oliver-Smith 2009; Cernea 1999; De Wet 2009). Whiteford and Tobin (2004) provide a comprehensive review of cases showing that, "even though the literature on natural hazards and disasters provides ample evidence to suggest that there are significant political, economic, social and physical consequences to resettlement policies… resettlement remains a 'popular solution to hazard and disaster management' (Chan 1995: 22)" (p. 190). Oliver-Smith

(1991) reviews cases in Turkey, Iran, Peru, and Guatemala to pinpoint specific aspects of each effort that contributed to either successful and unsuccessful results--one of the most important being public engagement and beneficiary participation in project design and implementation. Macías and Aguirre's (2006) analysis of relocation efforts at Colima volcano in Mexico points towards similar conclusions. Lack of community participation and a top-down, government-mandated approach led to major social conflict. Reluctance to move was also attributed to small home size, poor ventilation, inadequate construction materials, close proximity to other homes, and a general poor design—all aspects that "violate the customs of the people affected by disasters" (Macías and Aguirre 2006). Usamah and Haynes (2011) similarly conclude that relocation efforts at Mayon volcano in the Philippines did not consider broader livelihood concerns, meaningful beneficiary participation, disruption of social networks, nor culturally appropriate housing design. It therefore did not achieve institutions' nor residents' desired goals.

A well-studied, Latin American case occurred at Tungurahua Volcano near the town of Baños, Ecuador where evacuation and relocation experiences resulted in varying perceptions of success. The volcanic activity and subsequent emergency management crisis made residents, authorities, and aid institutions acutely aware of each entity's opposing attitudes regarding evacuation and relocation (Lane et al., 2004). Relocation was the preferred institutional response and, according to the institutions' own analyses, was successful; however some residents have very different, opposing sentiments (Tobin and Whiteford, 2002). It may seem intuitive to suggest that relocation is the most effective strategy to completely reduce a population's susceptibility to volcanic hazards—a disaster can only occur when society and a hazard overlap in space and time. While efficient at reducing physical exposure to most hazards, relocation efforts that fail to consider factors influencing social vulnerability can result in "serious, and often permanent, socioeconomic and cultural suffering and impoverishment" for the resettled population (De Wet 2009: 78). Whiteford and Tobin discuss how in the Tungurahua Volcano case "emergency evacuation and resettlement policies unfairly hurt the most vulnerable populations, the poor and the disenfranchised. Such policies are unhealthy

because they make it more difficult for families to recover economic losses [and] separate them from their kin and support networks" (2004: 189).

The challenges of livelihood disruption faced in Baños are similar to those encountered by residents of Verapaz, El Salvador. Verapaz is a town of roughly 4,000 residents at the base of San Vicente volcano in an area of steep drainages prone to debris flows and flooding. In both cases, residents were reluctant to leave their homes. In Verapaz, the reasons for mixed relocation success stem from residents' reluctance to abandon their supportive social networks and livelihoods, among other relevant concerns detailed below. Increased social and livelihood challenges in the resettlement dissuaded residents living in high-risk areas from moving to new, free housing. For many residents who did move, social vulnerability increased as families were cut off from support. As Oliver-Smith (2009) notes, resettlement initiatives designed to avoid disasters can and often do result in unintended "development disasters."

In contrast to top-down implementation of the resettlement by the El Salvador Ministry of Housing and Urban Development, other DRR efforts led by Civil Protection, the Universidad de El Salvador, and various NGOs included broad public engagement in hazard monitoring and risk communication. Public participation in community-based risk reduction can empower stakeholders by forming partnerships with NGOs, universities, and other agencies, which can "improve the community understanding and stimulate the willingness to build the culture for disaster prevention and preparedness (Karnawati et al. 2011: 153). Successful community-based early warning systems (CBEWS) are well-documented: Indonesia (Fathani et al. 2014; Karnawati et al. 2011), Philippines (Allen 2006), Italy (García and Fearnley 2012), and Colombia (Coll 2013). The close collaboration of DRR institutions in San Vicente allowed for strategic, well-funded education and training opportunities for local residents to form a CBEWS. These systems focused on communication during emergencies and empowered local observers to gather information and transfer knowledge around San Vicente volcano. Unlike the relocation cases discussed above, the CBEWS programs do not significantly disrupt people's social and economic lives.

3.2.2 Geophysical Vulnerability in El Salvador

El Salvador is located in Central America above a subduction zone at the juncture of the Cocos and Caribbean Plates (Figure 3.1). The tropical climate, along with its geographic location, makes it at risk for a variety of geological and hydrometeorological hazards, including: earthquakes (e.g., 1986, 2001), volcanic eruptions (e.g., 2005, 2013), floods (e.g., 2009, 2011), landslides (e.g., 2005, 2009), debris flows/lahars (e.g., 2005, 2009), tropical storms/hurricanes (e.g., 1998, 2005, 2009), droughts (e.g., 2001, 2012), and tsunamis (e.g., 1902, 1957). El Salvador is frequently ranked in the top ten countries most susceptible to natural hazards by the United Nations and often ranks in the top three (CEPAL 2010). Ninety-five percent of the Salvadoran population are at-risk of some hazard, according to a 2010 report by the United Nations, and the World Bank ranks the Salvadoran population as the second most exposed to "relatively high mortality risk from multiple hazards" (UNDAC 2010; Government of El Salvador 2009; Dilley 2005; World Bank 2006).

El Salvador's precarious geographic location presents many hazards, but other countries exposed to similar hazards (e.g. Chile, Colombia) do not experience comparable disaster losses (De Greiff and Shashank 2012). Frequent experience with costly disasters has not necessarily translated into improved hazard mitigation in El Salvador, nor have DRR institutions succeeded in adequately preparing populations to face hazards and their consequences (Wisner 2001; Bowman and White 2012).

3.2.3 Social Vulnerability in San Vicente

El Salvador's colonial and political history shapes the rural poor's extreme situation of social and geophysical vulnerability. El Salvador was a Spanish colony from the early 1500s to the early 1800s, and *criollo* elites ruled large estates, establishing dominance over indigenous populations. El Salvador's economy has been predominantly based on agriculture. The early colonial *sistema de encomienda* (system of entrustment) was the Spanish crown's method to establish and maintain the Spanish *criollo* and *mestizo* elites' dominance in all facets of Salvadoran life and inhibit the indigenous population's upward mobility (Boland 2001: 16). *Encomiendas* allowed control over

large tracts of arable land that left the indigenous populations with one option— forced labor for the elite. The encomienda system "quickly degenerated into slavery" (Boland 2001: 16).

After independence from Spain in 1821, elite landowners occupied the fertile lowlands in order to maximize production of indigo. Processes of elite land tenure further marginalized indigenous populations by pushing them to less-desirable and more hazard prone areas like steep ravines and stream banks (Wisner 2001: 254). In the mid-19th Century, indigo was replaced by artificial dyes and demand for coffee rose (Williams 1994: 71). Finally, in 1881, any communal and State land that remained for use by rural Salvadorans was expropriated to elite families. The national government determined that the communal land system "impedes agricultural development, obstructs circulation of wealth, and weakens family bonds and the independence of the individual;" therefore, peasant farmers were instructed to forfeit their private land titles at which point they could be sold at "public auction to the highest bidder" (Williams 1994: 74). Fertile volcanic slopes were quickly repossessed from indigenous communities for coffee production, which once again dispossessed the Salvadoran poor from their lands. During this period, Haggarty describes that policy-makers:

> generally agreed on the promotion of coffee as the predominant cash crop, on the development of infrastructure (railroads and port facilities) primarily in support of the coffee trade, on the elimination of communal landholdings to facilitate further coffee production, on the passage of antivagrancy laws to ensure that displaced campesinos and other rural residents provided sufficient labor for the coffee *fincas* (plantations), and on the suppression of rural discontent (Haggarty 1988: 1).

The resultant social structure further concentrated wealth and power and ensured that access to education, land ownership, social works, and healthcare were kept out of reach of the oppressed majority (Haggarty 1988: 1). (Wisner 2001: 252–253) describes that "the poor majority have been scratching out a living on tiny plots while selling their labor to the coffee barons" or forced to migrate ever since the 1881 expropriation of land.

Inaccessibility to land, extreme economic inequality, and a political system favoring the wealthy led to uprisings, rebellions, massacres, and most recently a 12-year-long civil conflict (1980–1992) which killed 75,000 people (Wisner 2001; Wood 2003:

23, 56). At the start of the war in 1980, "90% of all farms were less than five hectares, and six families held more property than the 133,000 smallest-scale farmers" (FUSADES and The World Bank 1998: 194). Though some land tenure reforms were established throughout the war to appease combatants, meaningful advancements were not achieved until the 1992 Peace Accords. Even these reforms were plagued by "delays in implementation, disgruntlement concerning the quality of land to be transferred, high land prices, and not surprisingly, political tension" (FUSADES and The World Bank: 197). This political and socioeconomic reality perpetuates Salvadorans' physical and social vulnerability to natural hazards and limits their overall resilience when facing hazard events.

Around San Vicente, the fertile volcanic soil, centralized location, and proximity to the Lempa River make this area an agricultural hub. For these reasons, much of the territory has been managed and/or owned by the wealthy elite since colonization. Presently, the higher elevation is dominated by coffee crops, while the fertile bottomlands are used for sugarcane production. Hence, the poorest residents in Verapaz have settled on the high-risk banks of the *Quebradona* Creek. Many *Vicentinos* (people from San Vicente) comment that, "El volcán es de Cristiani"—referring to the fact that nearly the entire volcano is owned by former president Alfredo Felix Cristiani Burkard serving his coffee production enterprise.

3.2.3.1 Community and Livelihoods in Verapaz

In order to understand why the communication, education, and monitoring strategies implemented in Verapaz succeeded while the resettlement did not achieve anticipated outcomes of planners, the reader needs some socio-cultural background on the community fabric and livelihood strategies of the residents. The structures of community support and livelihoods that exist in Verapaz are an adaptation to the circumstances of geophysical and social vulnerability described above. These adaptations help explain how these people can live in precarious circumstances.

In 2009, the ethnically homogeneous, *mestizo* population of Verapaz municipality was 6,257, the majority of whom live in and around the town center and government seat

in Verapaz (Fundación Intervida 2012). The town is connected to the departmental capital city (San Vicente) by a paved highway on which public transportation runs regularly. There is a municipal government, public health clinic, school center, civil court, National Civilian Police office, and Cultural House that all form the base of institutional support and helped provide services after the 2009 disaster. No formal community organizations are registered with the municipal government in Verapaz; therefore groups that have formed cannot benefit directly from governmental financial support. Similarly, there are no organized governmental or institutional efforts to help diversify livelihoods, strengthen entrepreneurship, or support economic growth or local production of goods. There are four economic-oriented community groups that support sugarcane production, basic grain production, egg production, and women's sewing projects; however no group has an annual budget or outside support (Fundación Intervida 2012).

Livelihoods in the town of Verapaz largely revolve around agricultural activities dominated by a male workforce. Families often rely on women, however, to help diversify livelihoods and income generating activities on top of their unpaid labor in the home. In addition to ensuring a smoothly run family unit, women are largely responsible for small-scale animal husbandry, operating corner stores, producing and selling dairy and sugar-cane-based products, and making and selling corn tortillas. One hundred and fifteen families maintained cows and small-scale dairy production operations, and 85% of families possessed one to three animals. Household production of chickens, eggs, pigs, and goats is commonplace and culturally valued by the women who manage these activities. Downtown Verapaz is peppered with small mini-mart stores, hardware and agricultural supply businesses, seamstresses, shoe repair shops, and a couple of household-run *pupuserias* (restaurants)—many of which are overseen by women. Importantly, some families are supported through the more recent influence of *remesas*—financial support sent from (mostly male) family members that live and work in the United States and other countries. In Verapaz, an estimated 10% of families receive monies sent from the U.S. to help with daily living expenses, which are often managed by women (Fundación Intervida 2012).

The vast majority of wage earners are employed as day-laborers by larger landowners, and they are considered poor working class (Cabrera and Amaya 2015; Fundación Intervida 2012; San Vicente Productivo 2001). Of the 18 departments in El Salvador, San Vicente Department has the highest concentration of individuals living in extreme poverty (Cabrera and Amaya 2015). In Verapaz, larger land holdings ranged from 11.5 acres (14 hectares) up to hundreds of acres and are concentrated among just 19 households who use them commercially for coffee and sugarcane production or rent plots to local residents (Fundación Intervida 2012). Individual farmers who are not wage laborers rent plots of land from large landowners to plant corn, beans, maize and other vegetables. Many of these small-scale farmers are forced to pursue unfavorable credit options from powerful lending institutions or individuals to pay for access to land, seed, fertilizer, and pesticides (Fundación Intervida 2012). Some are also able to claim small plots of land close to steep drainages to cultivate for market and subsistence needs. More than half of the 934 total farmers in Verapaz cultivate less than 1.16 acres (1.4 hectares) of land for their households' use (Fundación Intervida 2012). One resident day-laborer describes typical farm life in Verapaz:

> *Here we pretty much all do the same…most of us work as campesinos, day-laborers. Maybe a mother had a son in the United States who sent money, but most of us struggle and work in the* [coffee] *fincas. Or in the cane fields. Cleaning and fertilizing coffee. All of the big fincas are there. He who doesn't like to go to the fincas goes to cut sugar cane or work in the sugar mills. We have to work, even though it doesn't pay well, for food… Here we kill ourselves working. But the profit is for the "Big Guy"—the one who controls the monopoly.* – Interview 1 (Male, mid-30s)

This current reality of land availability and ownership are indicative of the historical colonial influence that still plays a major role in livelihood realities for rural farmers. To this day, Salvadorans frequently refer to the influence of "The 14 Families"—an influential group of elite families believed to dominate social structure and politics throughout El Salvador for generations (Haggarty 1988). As of 2009, the poorest 20% of Salvadorans earned only 3.71% of total income shared in the country (ranking 116th in income inequality out of 156 countries) (IndexMundi 2014).

The towns of Verapaz, Guadalupe and Tepetitan are currently situated near drainages or directly on top of past debris flow deposits. Citing the inherent danger of living in close proximity to natural drainages, Civil Protection and the National Assembly passed a law in 2003 prohibiting construction and development of land in close proximity (50 meters) to active (or potentially active) drainages (Viceministerio de Vivienda y Desarrollo Urbano de El Salvador 2003). This land is legally “protected” and off limits for ownership and development. However, in San Vicente department this law was not enforced. For poor, landless Salvadorans, squatting in these precarious locations for living and farming practices became their only viable option, which increased exposure to lahar and flood hazards.

This history of unstable land tenure is so deeply entrenched that it continues to be accepted—or at least expected—by Salvadorans. Ties to land and agricultural practices run deep—not because rural farmers pass down large parcels of land from one generation to the next, but because families carry on livelihood practices that have sustained them for centuries. In this largely subsistence and wage-laborer-based agricultural tradition in Verapaz, families, neighbors, and friends are often supportive of one another to help meet basic needs.

Vicentinos have developed diverse livelihood and social networks in the face of systemic marginalization and oppression. These coping strategies benefit tight-knit communities throughout daily life and in times of hardships, war, and disasters. Most importantly, these networks persist today. Residents describe the importance of their family and neighbors during hazard events, and also exhibit their own collective agency to make decisions contrary to institutional plans or directives.

Residents largely describe a supportive, extended family-based structure that provides necessary assistance during times of need and enforces safety and security within the community. Many families are multi-generational and occupy the same residences. These assistance networks were crucial, as survivors reflected on the reliance of family and trusted neighbors that provided rescue, aid, lodging, and basic goods during and after the crisis. The tightly-knit social fabric defining community resilience in

Verapaz is fundamental for weathering adversities born by social and economic inequality, as well as those provoked by hydrometeorological events.

3.3 Methods

This study is based on experiences of residents affected by the 2009 lahar disaster but incorporates analysis of institutional interventions realized in the region during the months and years after the event. Understanding social dynamics (historical, organizational, political, and cultural) and clearly identifying which strategies are currently being used by institutions in El Salvador to reduce disaster risk were key components to the study. Field observations, review of literature and primary documents, and in-depth, qualitative interviews of targeted populations regarding the disaster and crisis management experience were collected in San Vicente and Verapaz during a 15-month-long field season (April 2011 – June 2012) for this ethnographic research project.

A total of 38 in-depth, semi-structured interviews were conducted with four, unique target groups:

- Uninhabitable Zone Residents (12 Interviews)
    - Most houses in this area were completely destroyed by the lahar, but 13 homes (though heavily damaged) remain standing and are occupied, even though the Ministry of Housing declared this area legally "uninhabitable." One family living in this zone opted not to participate.
- High Risk Road Residents (7 Interviews)
    - This is one of several areas located in southern Verapaz deemed "high risk" but is unique as some houses were completely destroyed or heavily damaged in 2009. Though the area was heavily affected it was never formally declared "uninhabitable." Eight homes remain and are occupied. One family living in this zone opted not to participate.
- Relocated Residents (8 Interviews)

- These interviews took place in the new settlement, New Verapaz. Four were conducted with residents in permanent homes, and four in temporary homes awaiting permanent homes.

● Disaster Risk Reduction Institution Representatives (11 Interviews)
  - These interviews were conducted with representatives from institutions (governmental, non-governmental, academic) working on disaster risk reduction initiatives in the region.

New Verapaz was designed to meet housing needs for 244 affected (or potentially affected) families that lie within the 50 meter boundary of an active (or potentially active) drainage. Most of these families did not experience a direct impact from the 2009 disaster, but the Ministry of Housing and Urban Development sought to avoid future disaster impacts for these at-risk areas. Hence, several other less-affected neighborhoods downstream the *Quebradona* Creek were deemed "high risk," and these families were offered a new home and encouraged to move. The sample for this study focuses on nearly all of the families within the "uninhabitable" and "high-risk" zones of Verapaz that were devastated in 2009, as these families would seemingly have the most interest in moving to a new settlement. All of these families have either stayed in their original (often damaged) homes or relocated to New Verapaz but decided to move back to their old "high risk" homes.

The interview guide was developed by both authors and a professor at the Universidad de El Salvador, then further modified as relevant themes emerged throughout interviews. The structure of the interview guide was open-ended so as to minimize researcher bias and to allow for a relaxed conversation that could expand and contract based on the interviewee's comfort with the topic (Morgan et al. 1992; Kempton 1996). The goal of these interviews was to better understand residents' ties to their land, reasons for leaving or not leaving their homes during and after the disaster, reasons for accepting or not accepting homes in the resettlement neighborhood, and experiences (past and current) in working with relief and development institutions that arrived to the region after the 2009 disaster.

All interviews were conducted in Spanish (occasionally alongside a Salvadoran field assistant) and digitally recorded. I (first author) or a Spanish-speaking assistant then transcribed each audio file verbatim. Each transcribed interview was subsequently coded using Atlas.ti software in order to more effectively "search for patterns in data and for ideas that help explain why those patterns are there in the first place" (Bernard 2013 *taken from* Saldana 2009: 8). A combination of descriptive and values coding was used in order to both "document and categorize" a wide range of varying experiences and opinions from the interviewees but also to "capture and label subjective perspectives" from each participant from the highly variable backgrounds of the aforementioned target groups (Saldana 2009: 6–7). Codes were established for each of the transcribed interviews, based on researcher and informant categories. For example, the broader categories of "Relocation" and "Livelihoods" contain many subcategories and codes (Table 3.1). And these subcategories were further broken down to identify patterns and differences between informants on these topics.

Table 3.1 Example categories, subcategories and codes for data analysis

Category: Livelihoods	**Category: Relocation**
Subcategory 1: Agriculture	Subcategory 1: Chose to Relocate
Code: Land Owner	Code: Relocation Challenges
Code: Land Renter	Code: Relocation Reasoning
Code: Day-laborer	Code: Relocation Rights
Code: Sugar-cane	Code: Relocation Benefits
Code: Coffee	Code: Relocation and Livelihoods
Code: Vegetables (Corn, beans, other)	Code: Relocation and Kinship Networks
Code: Wages, Loans, Taxes	
Code: Affected by 2009 Disaster	Subcategory 2: Chose not to Relocate
Subcategory 2: Small Business	Code: Challenges to Old Verapaz
Code: Resources Available	Code: Reasoning
Code: Credit/Loans	Code: Lahar Hazard Awareness
Code: Affected by 2009 Disaster	Code: Legal Ramifications
Code: Impacts Post-Ida	Code: Livelihoods in Old Verapaz
Code: Relocated	Code: Kinship Networks in Old Verapaz
Code: Not Relocated	

I (first author) translated each quote used throughout this paper. Field notes taken during each interaction with interviewees were used to complement audio file data. Similarly, I attended a variety of community events, institution-sponsored risk reduction projects, planning meetings, UES-FMP-sponsored DRR courses and workshops, crisis simulations, and an actual emergency (Tropical Depression 12 E, Oct. 2011), which permitted rich opportunities to employ the ethnographic tool of participant observation and acquire key documents on DRR programs. Field notes and key documents were also coded for themes and integrated with the categories determined from the interview data. Participant observations were used to triangulate the different data sets.

Interview sampling methods varied between the three target groups. Nearly all of the residents of the uninhabitable zone (12 interviews) and high-risk road (7 interviews) who refused to move to Nuevo Verapaz were interviewed. In Nuevo Verapaz, the sample was initially purposive, as it was important to capture perspectives from residents who had moved into their permanent homes (4 interviews) as well as from residents who were still in temporary, pre-fabricated homes (4 interviews) awaiting completion of their permanent home (Bernard 2013: p. 164 – 167). Key informants (11 interviews) from institutions doing DRR work were chosen based on the first author's interaction and rapport with them over the course of the field work, the informant's expertise and interest in the study, and their involvement with different risk reduction interventions in the region. Participants in this group include faculty from La Universidad de El Salvador – Facultad Multidisciplinaria Paracentral, the coordinator and technicians from Civil Protection (municipal, departmental, and regional levels), National Civilian Police, the coordinator and technicians from The Center for Disaster Protection (CEPRODE), and United Nations volunteers.

3.4. Results and Discussion

In response to the 2009 disaster in Verapaz, hazard monitoring strategies improved and a new settlement was built for relocating people living in at-risk zones. The analysis detailed below explains the state of hazard monitoring before and after the 2009

disaster; in brief, communication of hazards improved between DRR experts and local residents, which was demonstrated in a subsequent 2011 emergency. The resettlement project, which aimed to permanently remove residents from at-risk zones and provide them with new homes in New Verapaz, did not meet its goals entirely. Instead the at-risk zones remained fully inhabited, even as New Verapaz filled up with occupants. These unanticipated outcomes reflect the lack of consideration for local livelihoods, social networks, and connections to home when planning the resettlement project. Because the impact of relocation on these aspects of life in Verapaz was not explicitly considered, some families founds their social vulnerability was increased in some ways, while others were able to take advantage of new resources to come up with their own hazard mitigation and improved socioeconomic strategies. Both the hazard monitoring and relocation projects focused primarily on geophysical vulnerability—getting people out of the path of the lahars. This understanding of vulnerability lent itself well to increased local participation in monitoring and planning for future lahars or other hazards; however, this was not so straight forward in the case of the resettlement project, which also required serious consideration of factors contributing to social vulnerability.

3.4.1 Disaster knowledge of authorities and at-risk populations: Before and after 2009

Salvadorans' extreme vulnerability to natural hazards is well-known among practitioners and authorities, but hazard knowledge is not disseminated to at-risk populations or even local authorities tasked with disaster preparedness and response. On the other hand, evidence also shows that residents did not communicate past experiences with disasters to practitioners and institutions before the 2009 lahar disaster. A complete lack of preparedness, little awareness, and no institutionalized measures for early warning or evacuation contributed to the human and material losses during the disaster. However, improvements in disaster knowledge and communication started to be implemented after the 2009 disaster; the success of these changes was demonstrated by the community response during Tropical Depression 12E in October 2011.

A prime example of hazard knowledge that was never shared with the at-risk population is the case of a comprehensive, country-wide volcanic hazard assessment conducted in 2004. This effort by SNET and the U.S. Geological Survey (USGS) produced a hazard map for San Vicente volcano that defined possible inundations zones and high, medium, and low risk areas for lahars of hypothetical volumes (Major 2004). This work was published (albeit, in English) and made freely available online. For reasons not fully understood, this hazard map was never disseminated to the residents or authorities in any of the five municipalities on the northern flank of San Vicente volcano. There was no enforcement of the 2003 law prohibiting construction within 50 meters of drainages, and no other restrictions were applied in Verapaz concerning where people could build homes, regardless of the fact that past lahars had destroyed parts of the town and that the new map indicated that populated areas were at high risk for debris flows. In fact, according to residents, most were completely unaware that any hazard analysis had ever been conducted in the region.

> [The town] *disappeared, because they had never done a study. They had never done a study to see if the zone was habitable, but people needed homes, and they risked living so close to a drainage. Practically at the shore of the creek, the neighborhood was constructed...*[even though] *there were previous events.* – Interview 3

Similarly, the vast majority of respondents allude to their lack of awareness of the lahar hazard in Verapaz, and certainly *no one* was in any way prepared for the event that unfolded.

> *We never took it seriously, that it was possible that there could be such destruction…since no one ever told us that this had happened in the past, we didn't know…* – Interview 2

Though SNET was aware of lahar hazards in the region, information was not disseminated to municipal and departmental government institutions, including Civil Protection, as they were caught completely off-guard by the lack of warning and magnitude of the event in 2009.

> *The event took the government by surprise…afterwards, the government changed* [its approach]. – Civil Protection representative

It is important to reiterate that the three municipalities near San Vicente considered at high risk for volcanic debris flows (Verapaz, Guadalupe, and Tepetitán) have all experienced these hazards first-hand over the last 100 years. The January and February 2001 earthquakes leveled much of Guadalupe and Verapaz, and in August of the same year a debris flow killed one person and damaged infrastructure. In 1913 and 1934, debris-flow events destroyed a large portion of Tepetitán, for which it is now called Antiguo Tepetitán (Old Tepetitán). This area was abandoned, and survivors resettled at (New) Tepetitán, located a couple hundred meters away from the ruins of Antiguo Tepetitán. Likewise, deposits from this event covered southern Verapaz, destroying homes along the *Quebradona* Creek and killing many individuals. Memories of this event were, in some cases, orally passed to younger generations. Experience with recurring disasters, however, does not necessarily translate into increased awareness or adoption of preparedness measures.

> *Grandfather told us when he was just a few months old, the first one occurred…the first one occurred in 1913—in 1913 it happened. Later, the second one occurred around 1934. In '34, this town didn't suffer as much as in 1913. Actually, 1913 was very devastating…practically the same zone that was destroyed in 1913 is where it happened again in 2009.* – Interview 3

As the memory of the 1934 disaster faded, Verapaz's expansion slowly encroached to encompass the exact area destroyed in 1934. Some structures, including a new hospital/clinic and many houses, were actually built around large boulders deposited by the 1934 flow because they were too large to move. Entire neighborhoods were constructed on top of lahar deposits, even though elderly residents recall advising builders not to invade the areas closest to the drainage where the disaster occurred in 1934. Some study participants remembered these stories and warnings from the older generation, but only in hindsight after the disaster. Some also expressed their lack of understanding that past events could repeat themselves.

> *They say*—(aside) *I don't remember—that in 1934 the volcano washed out, and a large part of Tepetitan was lost with a large part of San Vicente. There was evidence that something had come down* [the volcano]. *That was in 1934…the people, the new generations—no one believed that another situation would occur. We have personally lived it, and know that it can.* – Interview 10

Notably, representatives from DRR institutions were not aware of residents' past accounts and oral histories. Indeed, most residents acknowledge that past disasters were not openly discussed or considered prior to the 2009 event. This fact represents that there has also been a communication disconnect of local hazard knowledge held by residents that was not openly communicated to scientists and authorities, exposing a two-sided hurdle in risk communication and risk reduction.

3.4.2 The 2009 Event and Official Response

The 2009 lahar disaster at San Vicente volcano made evident the risk communication and risk reduction problems outlined above. In the end, the disaster spurred the Government of El Salvador (GOES) to expand Civil Protection-led efforts and hire dozens of technicians who were trained and strategically placed in the most at-risk communities. In San Vicente, Civil Protection was free to partner with local GO and NGO institutions to strengthen their own capacity to engage local residents in education, preparedness, and training efforts in order to incorporate them into hazard monitoring activities. The GOS demonstrated its support to the victims through this expansion of Civil Protection. The Ministry of Housing and Urban Development also created a relocation scheme after the 2009 disaster to reduce the risk of people living in government-declared uninhabitable and high risk zones.

Between 11:00 pm – 3:00 am local time (UTC – 6 hours) on November 7–8, 2009, a low-pressure system related to Hurricane Ida caused intense rainfall (355 mm over a period of five hours) that triggered shallow landslides and deadly debris flows on the northern flank of San Vicente Volcano in Central El Salvador. Lahars inundated neighborhoods of towns in five municipalities (Guadalupe, Verapaz, Tepetitán, San Cayetano Istepeque, and San Vicente) killing more than 250 people and destroying between 130 – 200 homes (Figure 4.2). Though five municipalities encompass the northern flank of the volcano, the town and municipal center of Verapaz immediately became the symbol of the tragedy due to the impressive images of the damage and the tragic stories told by survivors (Figure 4.3).

Figure 3.2 Five affected municipalities encompassing the northern flank of San Vicente Volcano. Inset of Verapaz and New Verapaz, modified from Google Earth (2012).

Figure 3.3 Aftermath of lahar destruction in Verapaz (Photo Credit: Jose Fredy Cruz Centeno).

Lack of warning and effective preparedness, and the timing and magnitude of the event all exacerbated disaster losses. Rescue and recovery efforts in the immediate aftermath of the disaster provided survivors with shelter, food, clothing, and healthcare. National and international development and aid institutions quickly conducted needs assessments to identify how to best provide for the affected areas and determine longer-

term strategies to reduce vulnerability to future disasters (CEPAL 2010; Duran 2010; Government of El Salvador 2009).

Aid poured into the region to help with the short-term recovery effort, and plans for the resettlement in New Verapaz (two kilometers northeast of Verapaz) and additional DRR efforts followed (see inset Figure 2). Survivors reported positive experiences with the generosity offered by volunteers and aid organizations that provided food, clothing, and shelter. In the department of San Vicente, 130 – 200 homes were completely destroyed, so four existing structures (two schools, one church, and one community center) were converted into provisional shelters. Most families reported living in shelters from a few weeks up to three months.

As response and aid distribution shifted from meeting basic needs to a longer-term solution to reduce risk, the Ministry of Housing and Urban Development declared that homes located within 300 meters on either side of the *Quebradona* drainage were "uninhabitable." This decision immediately made 234 homes off-limits, and most of these families represent the most vulnerable sector of the population that had encroached into dangerous areas (Aguirre 2011). Many families resisted this policy decision—not only the families affected in 2009 but also many who were not directly affected but fell within the 300 meter "uninhabitable" range. To mitigate backlash and provide a more permanent risk reduction agenda, the Ministry of Housing and Urban Development purchased a parcel of land outside the high risk area for the construction of New Verapaz--a proposed settlement of 244 homes for affected residents located two kilometers away from Verapaz (Aguirre 2011; Gobierno de El Salvador 2010). Money for the land purchase and settlement construction was donated from the United Nations Development Program (UNDP), the Panamanian Embassy, Oxfam, UNICEF, the Italian Episcopal Conference, and the municipal government of Verapaz, and costs exceeded 5.4 million (USD). Government-issued announcements describe the overall goal of the resettlement project to "provide housing and new habitat for families" and meet "minimum basic conditions" for "humble, affected families" but mention nothing regarding community participation, livelihood considerations, or preservation of social networks (Ministerio de Vivienda y Desarrollo Urbano 2013a; Ministerio de Vivienda y Desarrollo Urbano 2013b).

In May 2010 (six months after the disaster), 60 families who had not made their own housing arrangement (temporary or permanent) or had not reoccupied their damaged homes were chosen randomly and given the opportunity to reside in temporary, pre-fabricated homes constructed at the site for New Verapaz (Figure 3.4). These 60 temporary homes fell far short of the 244 permanent homes the government promised (Aguirre 2011). Slowly, however, the temporary settlement evolved into the permanent solution designed by the Ministry of Housing and Urban Development. Eventually, families that completely lost their homes during the disaster or lived in homes within the confines of the newly designated "uninhabitable" area were offered a new, permanent home in New Verapaz. Groups of homes were constructed in phases, and this process took years. When a house was finished, a lottery was held to determine which family in the list of beneficiaries would receive the house. The vice-minister of Housing and Urban Development, Jose Roberto Gochez, celebrated commencing the final phase of construction in October 2012 by announcing that "the initiative will benefit 244 families, which in the coming months can count not only on adequate housing but a fully developed habitat" (Ministerio de Relaciones Exteriores de El Salvador 2012). The last batch of 123 permanent houses was not completed until March 2013, more than three years after the event (Ministerio de Vivienda y Desarrollo Urbano 2013a).

Figure 3.4 Resettlement homes in New Verapaz (Photo Credit: Ministerio de Vivienda y Desarrollo Urbano 2013a).

Even the President of the Republic, Mauricio Funes, indicated that a change needed to be made in order to avoid future disasters. Five months after the disaster, he addressed the communities of Guadalupe and Verapaz to reassure them that the disaster and the institutional shortcomings will not be repeated in the future.

> *We promise you, through government support, that new natural disasters will not have the same tragic consequences of [Tropical] Storm Ida. I have assured you personally…next time, institutions will not react the same, and we will not improvise and risk the lives of entire communities by not giving priority to risk prevention…*– Mauricio Funes, President of El Salvador (Funes 2010)

For this reason, the 2009 disaster marks a "before and after" in terms of DRR in El Salvador. It was immediately recognized that the emergency overwhelmed not only the ill-prepared public but also institutional capacity. Lack of awareness, preparedness, and a reliance on reactionary strategies were deemed unacceptable, leading to institution-driven initiatives to reduce risk in the region. Strengthening Civil Protection's capacity and training, hiring new community-based technicians, and closer collaboration with University of El Salvador investigations and NGO DRR initiatives were all improvements from the previous system. The Center for Disaster Protection (*CEPRODE*), the National Foundation for Development (*FUNDE*), the Municipalities for the Jiboa Valley (MIJIBOA), Caritas San Vicente Diocese, and a United Nations Development Program (UNDP) project all provided human and financial support to the broadened DRR strategy. An alliance of GO and NGO efforts have been effective at training local residents to monitor rainfall and calculate rainfall rates, better understand precipitation as a landslide/lahar trigger, and use a two-way radio communication network to report daily precipitation data and other observed changes (e.g., surface cracks) directly to the municipal Civil Protection technicians and others in the monitoring network. The results of these institutional efforts have improved hazard awareness and disaster preparedness, as demonstrated below in the response to Tropical Depression 12E in 2011.

3.4.3 Community-based early warning system effectiveness

The participatory approaches used by Civil Protection, the University of El Salvador, and a cadre of NGOs addressed the knowledge gap through inclusive training and education programs--especially for individuals who opted not to resettle and remained within the uninhabitable zone. These residents are now more vigilant to monitor quickly changing conditions that might indicate a possible lahar. Local monitors go upstream during heavy rains to check river levels and listen for landslides upslope or approaching lahars—information that they spread to the other residents awaiting news in their homes.

> *We are vigilant about checking on conditions, and we even go up to look at the stream to see how much water there is.* – Interview 20 with resident of uninhabitable zone who claimed a house in New Verapaz and goes there during heavy rains.

> *In Agua Agria and in San Emigdio my friends pass time on the computer and on Facebook and they tell me when it's raining. For whatever thing is happening, they warn me.* – Interview 20 with resident of uninhabitable zone who claimed a house in New Verapaz and goes there during heavy rains.

Part of this new awareness comes out of having seen first-hand and survived the destruction in 2009. But ongoing institutional efforts have strengthened Verapaz's and the surrounding communities' organizational capacity to monitor environmental conditions. Participant observation carried out by the first author during the training of local observers and during field trips and scientific campaigns showed that community participants are engaged in the scientific process. Observations of local observers' actions and attitudes during the management of a real crisis in 2011 and data gathered from the semi-structured interviews all establish that the partnerships between NGOs, the Universidad de El Salvador, and Civil Protection helped spark and maintain community-level interest in local monitoring initiatives. Rather than be passive recipients of information generated by unknown entities, local observers are actively involved in gathering data and making relevant observations while ensuring that the information is communicated to the authorities and the public.

Local observers within the CBEWS measure rainfall rates and communicate potentially dangerous conditions to local Civil Protection authorities via two-way radios. Observers also use the radios to communicate information to one another and to the

municipal hub in Verapaz. Information is then distributed via cell phones, SMS messages, social media, and during emergencies the local Civil Protection technician will communicate information and recommendations via megaphone throughout Verapaz.

Each municipality is equipped with a weather station, a communication hub, and a Civil Protection technician/liaison; and key actors are trained in standard operating procedures during emergencies. Residents are watchful and learn to recognize potential precursors and signs that might provide warning to future hazard events, such as lahars, landslides, and floods. Residents' decisions to temporarily relocate and evacuate the high risk zone during periods of heavy rain or during official Civil Protection warnings makes effective use of new training, increased awareness, and a safer space provided in New Verapaz. Institutional support has made these improvements a priority, and all of these steps have been realized *after* the 2009 disaster.

Tropical Depression 12E in October 2011 was the first time the Centers for Emergency Operations (COE) were activated. I (first author) was present during the entire, 12-day-long crisis and used participant observation, field notes, post-emergency reports, and targeted interviews with DRR representatives to analyze the effectiveness of the new emergency management strategy. Though participants' hypothetical roles and responsibilities were taught during a five-month-long emergency management certification course, Tropical Depression 12E occurred before trained individuals could participate in a scheduled emergency simulation exercise. The first real-life application of the training received occurred during the nearly two-week-long emergency presented by Tropical Depression 12E. The first two days after Civil Protection elevated the hazard alert level and activated the COE, Civil Protection and CEPRODE facilitated the designation of actors' management roles. Also, communication protocols were established between local observers, authorities, and the public. Throughout the following ten days of emergency management, the connection to the network of local observers proved invaluable at reporting data in near real-time, which allowed decision makers to evacuate at-risk residents in a timely manner. As active, trained participants in risk reduction, local residents and DRR institutions are better connected and rely on one another to correct some of the past communication and hazard awareness problems. The

new COE program was able to successfully utilize the close social networks of the Verapaz Community to communicate critical geophysical data, hazard warnings, and evacuation recommendations.

3.4.4 Mixed Success in Relocation Efforts

Differing understandings of priorities between outside authorities and Verapaz residents also played out in other medium and long-term assistance provided for disaster mitigation and recovery, particularly the Ministry of Housing and Urban Development's relocation scheme that developed. Relocation planners aimed to permanently remove residents from the uninhabitable and at-risk zones in Verapaz. This was not achieved, although alternate housing was provided and occupied by some extended family members from at-risk households, newcomers to the area, and some at-risk residents downstream whose homes fell within the 50 meter "high-risk" delineation. The results discussed in this section examine, from the viewpoint of families from the at-risk zone, how the resettlement project unfolded, what advantages and disadvantages they saw within the project, and how they came to decide where to reside. Based on their responses, a disruption of livelihoods, social networks, and ties to home were among the most common reasons why residents decided not to permanently relocate from their at-risk homes.

The relocation project design demonstrated a lack of awareness on the part of project planners about day-to-day survival and social vulnerability in Verapaz. Community "participation" in the project was limited to families' obligatory labor during construction of their new homes alongside the contractors hired by the Ministry of Housing and Urban Development. Because of the limited incorporation of local concerns and knowledge, the relocation project brought some unanticipated outcomes. Affected residents largely fall into four distinct groups. Some residents were forced to move to New Verapaz because there were no other viable housing options when their houses were completely destroyed. Other residents initially relocated to New Verapaz but returned to their original, at-risk homes in Verapaz. Another contingent used the relocation project to their advantage by claiming a house in New Verapaz with the intent of remaining in

Verapaz while renting the new house for additional income or gifting it to family members in need. Finally, there is a group of residents who remained in Verapaz and has no intention of relocating. The Ministry of Housing and Urban Development struggled to achieve desired objectives, because livelihoods, social networks, and strong ties to homes were not adequately considered during project design and implementation.

Except for homes that were completely destroyed and swept away from their foundations, nearly every other home left standing was cleaned out and reoccupied in the days and weeks after the disaster. Houses that were buried up to their rooftops in mud, boulders, and debris—houses where family members were killed—were patched up, swept out, and made livable. For outsiders (foreigners or national authorities/practitioners), it made little sense that residents would want to reoccupy their former homes after having experienced the trauma of the 2009 debris flows. A seemingly rational institutional response to the situation facilitated the hasty approval of the permanent relocation program by government authorities at the Ministry of Housing and Urban Development. Two actions were taken to facilitate this development project: 1) southern Verapaz was declared uninhabitable, which legally prohibited residents' reoccupation of homes, and 2) the construction of first temporary, then permanent homes in a new settlement—New Verapaz—where affected families could relocate.

Project implementers in the Ministry of Housing and Urban Development deem the initiative a success because each of the new homes is occupied. For the residents in New Verapaz, as described below, physical exposure to the lahar hazard has certainly diminished compared to living in high-risk or uninhabitable zones. However, occupation of these new homes does not mean no one is living in the high-risk or uninhabitable zones. Occupants of the new homes include not only relocated residents from Verapaz, but also outsiders who were able to get included on the beneficiary list, family members who have split off from multi-generational families residing in Verapaz, and residents new to the area renting the new home from families that have moved back to or stayed in Verapaz. In reality, the homes that were not totally destroyed in the uninhabitable zone and high-risk focus area are still nearly completely occupied, as residents are reluctant to relocate mainly due to disruption of livelihoods and unwillingness to abandon social

networks. The relocation initiative systematically (yet unintentionally) exacerbates social vulnerability for some households in both Old and New Verapaz, yet also opened some select opportunities for particular families that claimed additional free houses, rented newly claimed homes while continuing to reside in their old homes, or claimed a new home even though they were not affected in 2009.

The 19 families interviewed who have reoccupied their old homes do not live amongst the ruins of their old neighborhood in their original houses because they have no other option. A new home in New Verapaz was made available to each of them. The reasons behind their reluctance to move are rooted in social, cultural, and economic realities that dissuade the population from abandoning a deeply ingrained and advantageous system that offers strategies to cope with economic and social vulnerability. Livelihood disruption, deterioration of social networks, and strong ties to original homes are the main reasons why residents were reluctant to relocate.

3.4.5 Disruption of Livelihoods due to Relocation

Most reluctance to relocate revolves around the different ways this dramatic change would disrupt livelihood strategies. Since most families rely on agriculture, moving away from farmland proved difficult. New Verapaz is too far away from traditional agricultural lands, cherished homes, and other economic opportunities. Access to lands is not only important for convenience, but it is also important to be close to ensure that produce and animals are not stolen.

> *Our* [farm] *land is close, but leaving here for* [outer reaches of New Verapaz] *our lands would be too far away. We barely make enough to feed ourselves. Having to travel and pay for gasoline would take away any remaining profits.* – Interview 1 with resident of uninhabitable zone who chose not to relocate.
>
> *One of the advantages [*of living here*] is this is the zone we work. We work the land. If we leave, we leave everything behind, and it's taken years of effort. Thirty years we've been here, we couldn't leave. We stay here because this is where we have everything, and if we leave, we have to leave it all behind. We would have to start all over, alongside strangers, with a new lifestyle.* – Interview 1 with resident of uninhabitable zone who chose not to relocate.

Since homes and some plots are passed from generation to generation, the modifications and improvements are highly valued, especially since the investments required to make these changes take so much work. To abandon years of hard work and dedication to make a place "home" was considered unthinkable.

In addition, homes in New Verapaz are located off the main road and far away from the bus route, so unlike Verapaz very little business traffic arrives to household-run shops since there is no public transportation into or throughout the new settlement. Relocation meant an inconvenient commute for all residents, including wage laborers and women traveling to participate in market activities. Acquiring reliable transportation from New Verapaz to the main transportation routes in Verapaz proved to be too much for some residents. One relocated individual who decided to return to the uninhabitable zone explained:

> *Sometimes we got a ride [*out of New Verapaz*], but sometimes we had to have money to travel, unless we wanted to walk out on foot. Sometimes we found a ride to drop us off [*near Verapaz*], but afterwards, I said, "Its better if we stay here [*at our old house*]*. – Interview 2 with resident who relocated but chose to return to the uninhabitable zone

Increased distance is an inconvenience, but access to electricity and water are vital for many tasks that further diversify income generation. There was no electricity, and there were only communal bathroom facilities in New Verapaz, even two years after the completion of the first round of permanent houses.

> *Some of us never left* [our original home] *even from the beginning because there was no electricity* [in New Verapaz]. – Interview 2 with resident who relocated but chose to return to the uninhabitable zone.

> *I lived in the new settlement for a year. I lived there for a year because they said they would provide electricity and that we would each have our own bathroom, but that never happened.* – Interview 4 with resident who relocated but chose to return to the uninhabitable zone.

For families with diversified livelihoods running small shops that required power (e.g. seamstresses, dairy vendors needing refrigeration, corner store owners), it was impossible to run their business without electricity, which dissuaded small business owners.

> *There are people here* [in their old houses] *that have been given new houses there* [in New Verapaz] *but they don't go because the cheese spoils. There is no way to refrigerate.* – Interview 2 with resident who relocated but chose to return to the uninhabitable zone.

Also, gifted plots of land in New Verapaz are small (10 x 20 meters), especially when compared to the space to which residents were accustomed. Finally, homes are built right next to one another (Figure 4). There is no room in New Verapaz to have animals (e.g., chickens, cows, pigs, goats), which are highly valued in the local culture and help provide families with food and additional income.

3.4.6 Disruption of Social and Kinship Networks and Ties to Home

In addition to livelihood disruption, the unweaving of the tightly-knit social fabric was a major factor that dissuaded families from relocating. A lottery-type system was employed to help fairly distribute new homes. Similar problems with this style of housing distribution were documented in Turkey, as family units were randomly distributed throughout resettlement areas and received homes at different stages of the project (Enginoz 2004). This system, which was specifically engineered to avoid suspicions of political favoritism, had the unintended consequence of destroying familial networks. When families and neighbors were not allowed to move together as one unit into New Verapaz, moving meant that the social capital that this network traditionally provides was fractured. In the nearby Lempa River Basin, social capital was regarded by Bankoff et al. (2009: 82) as a major factor in "reducing vulnerability and an unavoidable starting point for risk reduction." Residents who had relied on family and neighbors for generations were suddenly forced to live apart in different regions of New Verapaz. New neighbors were sometimes complete strangers, as many of the people on the beneficiary list were homeless individuals who had flocked to the area in hopes of taking advantage of the assistances being offered to the affected population. Families relocated based on the "luck of the draw" lottery system rather than family and kinship units that defined community life in Verapaz.

During times of need, families and proximal neighbors support one another. In many instances, extended families and trusted neighbors occupied an entire block or

portion of a neighborhood. Whether it be watching the house while a family member was out of town or working the field, trading different food crops, babysitting or even sharing child-rearing responsibilities, this social support network was key to a smooth-functioning way-of-life. Relying on family and neighbors was considered necessary.

> *The truth is, with all of the other problems we have, we don't have people here looking for more problems* [delinquents]*—we don't allow it…life goes on and we live on. At least we survive. The truth is, if you need something but don't have it and I do, then we both get by. It's a form of co-existing.* – Interview 3 with resident of high-risk area who never relocated to New Verapaz.

> *People get along really well here, even more so after* [the disaster]*, we are even more like family. We are more united. It's OK if someone needs something—between everyone we find a way to solve it…I tried to live* [in New Verapaz] *but it was insufferable.* – Interview 9 with resident who relocated but returned to the uninhabitable zone.

Not only did the lottery prohibit extended family and neighbors to move together, the actual size of the new house was not conducive for multi-generational families. The new houses only had two small bedrooms, so the design of the home made it impossible for entire family units to move together. This is one of the primary reasons why newly provided homes in New Verapaz are occupied but existing homes within the uninhabitable and high-risk areas are also occupied by the same extended family. For many families, select members have relocated, leaving the other portion of the family behind because there is simply not enough space.

> *The mayor came here and told us to go to the new settlement. I told him "Yes" but only if they gave me the same size plot. He said, "No" and that he couldn't give me any more land. The lot is tiny. So I told him, "No thanks."* – Interview 1 with resident of uninhabitable zone who chose not to relocate.

In addition to plots and houses being small, houses are very close together, which has caused social problems.

> *We hear about problems with neighbors, that they don't get along. Remember that when you have houses like that, like in San Salvador, where one wall serves two houses—no way, man! They even know how you sleep, and it's terrible!* – Interview 3 with resident of high-risk area who never relocated to New Verapaz.

> *We are not accustomed to living this way, in these spaces* [closely spaced houses]. -- Interview 23 with relocated resident whose original house in the high-risk zone

was damaged but not destroyed.

This system not only divided familial networks, but it also brought to light a completely different problem—individuals and families from *outside* Verapaz who mysteriously appeared on the list of beneficiaries to receive houses. Local families continuing to live in their old homes frequently describe “aprovechados”—people from other towns that came to take advantage of the aid by saying they resided in the area but lost everything and are therefore deserving of a new, free house. A majority of interviewees explain that some of the first houses donated were, in fact, given to complete strangers that no one in Verapaz recognized. This resulted in major frustration and overall distrust in the process of project implementation, as well as cultivated suspicions of political favoritism—the very thing the lottery system claimed to avoid.

Some groups of families attempted to circumvent the lottery system by waiting to accept a new, permanent home. They are waiting until the very end of the lottery, even though they come up “next in line” to receive a new house. This reluctance is based on the hope that if they forego a home when their name is called, at the end of the project, the remaining families will all get to move together in the same area of New Verapaz.

Finally, residents repeatedly refer to their land as their “home”— it is where the family has lived for generations. As long as conditions do not improve in New Verapaz, there is no incentive to leave the area that is so familiar and has always proved sufficient to meet basic needs. Simply put, New Verapaz is not “home.”

> *I came back in May* [2010]*, and I felt at peace because this is where I have lived for so long…They gave me a provisional house, but I couldn't stand living there. Firstly, because there wasn't power. The house was very small. The sun was so strong, it was so hot in the afternoon—so hot. And the [communal] bathrooms were filthy…* – Interview 4 with resident of uninhabitable zone who relocated but returned to original home.

3.4.7 Relocation success

As noted above, a number of unintended outcomes resulted from the relocation scheme. In particular, some of these actually served as DRR strategies, although not in the ways that any DRR experts had intended. For example, the design of the resettlement effort and the distribution of homes at Nuevo Verapaz has unintendedly provided an

emergency alternative housing option for many of the families that have chosen not to relocate. Having friends, family, or tenants living in their donated house ensures that they have a place to go during emergencies.

> *Every rainy season we leave. When it gets bad, I leave—I pack my bag and I leave. I am scared, but I live here* [uninhabitable zone]. *When the rainfall is strong, I go* [to the new settlement]. – Interview 15 with resident of high-risk zone who claimed a new house but continues to reside in the original home.

> *People come back here* [uninhabitable zone] *because they feel more comfortable with everything they have in their homes. But in the rainy season, when the storms come, they leave running. A lot of people still run over there* [to the new settlement]. – Interview 19 with resident of high-risk zone who claimed a new house but continues to reside in the original home.

This partial relocation was clearly not the intended result of the new settlement, but at least during times of crisis, families are aware that they are in danger and flee to a safer area.

A successful relocation effort that fully removed people from at-risk zones might be attainable in El Salvador if certain criteria were met, including:

1.) A new home with lands equal to or better than previous conditions
2.) A guarantee that families, neighbors, and friends live in close proximity to each other, as was the case before the 2009 disaster
3.) Access to water, electricity, and sanitation facilities that are essential for healthy living and the needs of small businesses
4.) Proximity to farm lands
5.) Adequate space and permission to tend chickens, pigs, cattle, goats, etc.
6.) Easy access to public transportation.

However, these criteria were not met, and as a result, the portions of Verapaz that have been deemed uninhabitable are still occupied.

3.5 Conclusions

Throughout the world, relocation programs will likely continue since they can reduce or eliminate a population's spatial exposure to natural hazards. Success of these

programs, as suggested by this study, depend The Salvadoran national government and DRR institutions active in the region around Verapaz are making strides to reduce disaster risk within vulnerable Salvadoran communities. Financial, organizational, and human resource support invested in Verapaz and surrounding communities is making a positive contribution in terms of hazard awareness, education, and preparedness. Inter-institutional coordination between Civil Protection, the University of El Salvador, and a host of NGOs improved since 2009, and efforts are now undertaken collaboratively building off the expertise of each agency. The evidence gathered ethnographically in this study shows that institutions and residents are closing the communication gap that existed prior to 2009. These programs and this critical information focus primarily on community-based monitoring, open dialogue and improved communication between residents and authorities, and improved planning to reduce disaster risk.

Nevertheless, a more holistic understanding of vulnerability and risk--including both social and geophysical—was not incorporated by project implementers in Old and New Verapaz, and outcomes were of mixed success. In this case, project design and implementation reduced physical vulnerability for some but could not achieve broader success because livelihoods and social networks were disrupted by relocation. Had the project considered ways to reduce these impacts, residents would likely have been less reluctant to leave their high-risk settlement. In lieu of this, residents adapted the best they could, and some success was achieved by those who took advantage of the program design to help diversify livelihoods while providing alternative housing during emergencies. But many still live in the high-risk and uninhabitable zone with no alternative housing. Others have relocated, but found themselves cut off from vital livelihood resources and opportunities as well as crucial social networks. Providing basic needs, adequate living conditions, and proximity to livelihood activities in addition to allowing family and social networks to relocate together were the main factors that residents felt could have aided successful project implementation. Since these criteria were not met, many families that relocated have now returned to their original homes in the higher risk zones, and others never left at all.

Throughout the world, relocation programs will likely continue since they can reduce or eliminate a population's spatial exposure to natural hazards. Success of these programs, as suggested by this study, depend in part on how overall vulnerability (including economic, social, political, etc.) is reduced. Cultural and sociopolitical context varies from country to country and from community to community, making a stepwise, universal relocation "best practices" plan nearly impossible. However, there are some basic tenets that should be considered in order to achieve broader community buy-in. These are:

1) Access to livelihood activities
2) Continuance of social networks
3) Culturally appropriate housing that meets basic needs
4) Community participation throughout the design and implementation of the Project

This case study shows how historical land tenure and marginalization of the poor exposed people in Verapaz to the lahar hazard at San Vicente volcano, but that through these struggles important kin and social networks emerged to provide support to one another. While some DRR efforts, like CBEWS may find reasonable success even though they mainly focus on geophysical hazards, this history and these local adaptive strategies to social and geophysical vulnerability cannot be ignored in a relocation scheme. This case also shows the importance of understanding the dynamics and uniqueness of each population *before* implementing a relocation effort. That said, this approach takes time, money, political will, and institutional capacity, all resources in short supply in the immediate aftermath of a disaster.

List of abbreviations

CEPRODE – Centro de Protección Para Desastres (Center for Disaster Protection)

DRR – Disaster Risk Reduction

GO – Governmental Organization

NGO – Nongovernmental Organization

GOES – Government of El Salvador

SNET – Servicio Nacional de Estudios Territoriales (National Service for Territorial Studies)

MARN – Ministerio de Medioambiente y Recursos Naturales (Ministry of Environment and Natural Resources)

UES-FMP – Universidad de El Salvador – Facultad Multidisciplinaria Paracentral (University of El Salvador – Multidisciplinary Faculty of the Paracentral)

UNDP – United Nations Development Program

UNISDR – United Nations International Strategy for Disaster Reduction

USGS – United States Geological Survey

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Chapter 4: Field characterization of weathered volcanic slopes for rainfall-induced landslide potential: San Vicente Volcano, El Salvador

Abstract

Four years after Hurricane Ida triggered shallow, rainfall-induced landslides at San Vicente volcano in central El Salvador, two seismic refraction campaigns were organized to characterize weathered volcanic slopes proximal to the November 2009 failures and surface cracks that appeared post Tropical Depression 12E in October 2011. Prior field work and slope stability modelling conducted in 2012 at San Vicente volcano indicated that rising or perched water tables during heavy rainfall events could be a contributing factor to triggering shallow landslides. Field campaigns were conducted in May 2013 (end of the dry season) and sites were reoccupied in November 2013 (end of the rainy season) in order to capture seasonal changes in soil saturation with active seismic refraction methods. Three sites were selected for analysis. Results indicate repeatability in testing methods as similar refractors and velocities were identified in both campaigns at all three sites. P-wave velocities varied only slightly between both campaigns, indicating that, at least for 2013, saturated refractors were either not identifiable, did not vary in depth, or were too deep to capture with the methods used. Survey repeatability demonstrates that the methods used performed well in weathered volcanic slopes; however, future campaigns should be performed after particularly heavy rainfall events or combined with other geophysical methods like resistivity to better capture soil saturation changes.

Based on: Bowman, L., Richardson, J., and Gierke, J.S. Manuscript in preparation for submission. Field characterization of weathered volcanic slopes for rainfall-induced landslide potential: San Vicente Volcano, El Salvador

4.1 Introduction

Steep, volcanic slopes in tropical regions are highly susceptible to shallow, rainfall-induced landslides and debris flows/lahars (Frattini et al., 2004; Scott 2001; Scott et al., 2005). San Vicente volcano in central El Salvador experienced 355 mm of intense rainfall from Hurricane Ida rain over a five-hour period spanning 8-9 November 2009, culminating an already above-average rainy season. The hurricane rains triggered shallow landslides on the northern flank and quickly transformed into bulking debris flows (lahars) that filled channels and inundated low-lying areas of Verapaz, Guadalupe, Tepetitan, and San Vicente communities depicted in Figure 4.1. More than 200 people were killed (EM-DAT 2009), 75,000 persons displaced, and the disaster ranks as the third most costly in El Salvador's history with US$315,000,000 in damage (Tellman 2011; Bowman and Henquinet 2015; GOES 2009).

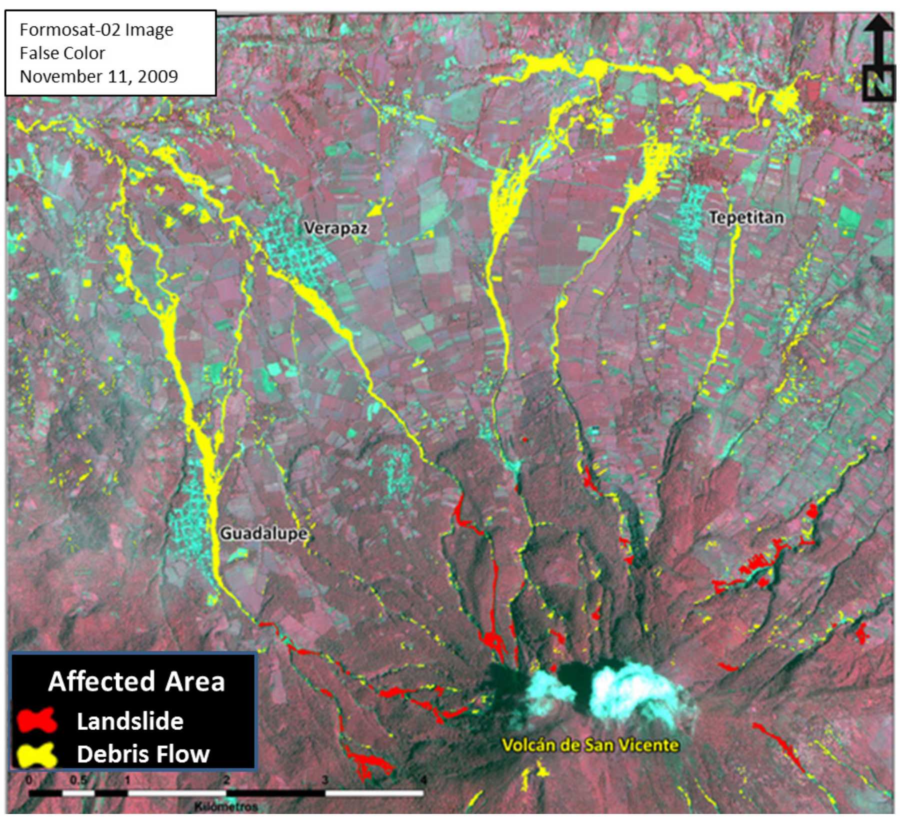

Figure 4.1 Landslides and debris flow inundation areas after Hurricane Ida, November 2009. (Modified from; SERVIR 2009). 13.595°N, 88.837°W, 2182 masl.

Even though five recorded lahars/landslides have occurred at San Vicente volcano over the last 350 years, very little research has been conducted to better understand rainfall-induced triggering mechanisms or educate at-risk populations to the hazards inherent to the area.

Smith et al. (2015) studied the stability of select slopes on San Vicente to determine the most important properties influencing the potential for failure. Naturally the steepness, mechanical strength, and water content were important variables for the slope stability. They also found that depth to the water table was critical in leading to conditions where the slopes were more likely to fail. A low-permeability bedrock layer contributed to conditions promoting a shallow water table in the relatively permeable unconsolidated materials. Field observations from 2012 and 2014 showed shallow bedrock was evident in some of the landslide scarps from the 2009 lahars.

Rainfall amounts from Tropical Depression 12E led to the appearance of surface cracks in some of the highest cultivated (coffee) slopes on San Vicente (Bowman et al., in review). These cracks and the intense rainfalls occurring in the vicinity of the previous lahar triggering events caused significant concern for local officials and residents (Bowman et al., in review). Confident assertions as to whether the cracks were superficial and benign or expressions of impending failures similar to the 2009 catastrophe were impossible to make due to the lack of understanding of the slope conditions. That is, were the slopes thin layers of loose unconsolidated deposits or thick; did shallow perched aquifers exist, etc.? While it was impractical to characterize all the slopes, we chose to conduct a sequence of focused field campaigns aimed at answering the shallow conditions (depths to bedrock and water tables) in select parts of the volcano. This paper describes time-lapse seismic refraction surveys performed on the northern flank of San Vicente volcano in 2013 with the goal of better characterizing slope lithology, water-saturation conditions, and the potential for perched aquifers by comparing time-lapse differences observed between the wet and dry seasons.

Little is known about hillslope hydrology after heavy rainfall that leads to slope instability. Rainfall duration and intensity are widely known factors contributing to slope instability, but a useful, tested rainfall threshold for forecasting purposes has not been

calculated for San Vicente Volcano. The national, departmental, and municipal governments realized that in order to make more effective risk-reducing decisions before, during, and after emergencies and issue timely warning and alerts, decision-makers need to be better informed about landslide/debris flow triggers. For this to be possible, establishing baseline data and initiating research efforts to better understand factors affecting slope stability were posed as necessary "first steps" for practitioners working in San Vicente.

4.2 Background

Seasonally perched aquifers forming above shallow, low-permeability fine-grained soil and/or rock layers have been identified as contributing factors that trigger landslides (Terlien 1998; Van Asch et al., 1999). No hydrological nor stratigraphy data exist at San Vicente Volcano. Its eruptive inactivity in a country with potentially dangerous active volcanoes has relegated San Vicente Volcano rather low in research priority. Even after the 2009 disaster, few research efforts have been directed at creating baseline data to better understand landslide triggers at San Vicente Volcano.

San Vicente Volcano has not erupted in the Holocene. Its thick soils are inter-bedded with ash layers from eruptions of nearby Ilopango Volcano, which has erupted *Tierra Blanca* ash deposits at least once since the last eruption of San Vicente. The ash layers have formed soils and been eroded and incised due to the tropical climate of El Salvador (Jibson and Crone 2001; Smithsonian-GVP 2013). Relatively impermeable basalt and basaltic andesite from old lava flows, and hydrothermally altered, fine-grained clayey layers may slow vertical drainage of the surficial soils. Sufficient saturation of these slopes may have potentially reduced the strength of the slopes and caused the onset of the failures observed in 2009 (Rolo et al., 2004). San Vicente Volcano (Chichontepec) has twin edifices, roughly trending East-West. The younger edifice is east of the older edifice. Though landslides have occurred on both edifices, the older, more-weathered western edifice has historically experienced more frequent shallow landslide/disaster events.

A post-disaster inspection lead by the Volcano Disaster Assistance Program

(VDAP) team from the United States Geological Survey (USGS) and El Salvador's Servicio Nacional de Estudios Territoriales (SNET) identified five major slope failures that caused supersaturated volcanic debris to flow into drainages and inundate communities on the northern flank of San Vicente Volcano (Schweig 2010). The physical characteristics of the relatively small landslides (1 – 3 m in thickness) permitted bulking as they flowed downslope, resulting in flow volumes between 100,000 – 350,000 m^3 (Schweig 2010).

Intense rainfall triggered the 2009 disaster (as well as the 1913 and 1934 disasters), so preliminary research to evaluate slope stability characteristics was conducted in May 2012 by Michigan Technological University Masters student Daniel Smith (Smith 2012; Smith et al. 2015) working with local governmental and non-governmental agencies and to lay the foundation for future work. Smith et al. (2015) used Rocscience slope-stability software and data collected during field work (Smith 2012) (grain size analysis and permeameter data) to evaluate the most probable slope failure triggers according to the precipitation and limited geological data available as inputs into the model. His findings revealed that depth to the water table was likely the most important factor affecting slope stability. Rising water tables throughout the wet season could reduce stress on steep slopes and be a triggering mechanism leading to slope failure. Their work suggested that the uppermost layer of soil is largely composed of ash and pyroclasts from neighboring Ilopango Volcano, and at very shallow depths these soils were extremely permeable and likely highly efficient at draining water down to impermeable layers (Smith et al. 2015). These preliminary conclusions pointed to a logical "next-step" in designing a method that would monitor water table/soil saturation migration between the dry and rainy seasons.

Just months after Smith's work, the Universidad de El Salvador – Facultad Multidisciplinaria Paracentral (UES-FMP), located in the town of San Vicente 8 km from the volcano, was awarded a small U.S. State Department-funded grant alongside Michigan Technological University (MTU) through the Partnership for Enhanced Engagement in Research (PEER) program to initiate baseline data gathering regarding landslide and flooding hazards for the region (Bowman et al., chapter 2). Together, with a

host of local institutions (Civil Protection, El Centro de Protección para Desastres (CEPRODE); The National Civilian Police, and local governments), research was directed to better inform decision-makers by studying landslide triggers and identifying lahar inundation zones. The MTU/UES-FMP research group determined that high-resolution, time-lapse seismic refraction surveys would be an appropriate tool to capture changes in water table depth and soil saturation, if implemented at the end of the dry and rainy seasons.

4.3 Methods

4.3.1 Site Identification and Survey Timing

The methods outlined in this work were chosen to capture details of the shallow subsurface. This investigation does not pretend to predict specific areas that might fail in the future, nor does it consider massive, sector collapse-type slope failures. A 2001 USGS report analyzing debris-flow hazards at San Vicente indicates that shallow landslides provoking small volume (100,000 – 300,000 m^3) lahars are most likely, which is precisely what occurred in 2009 (Major 2004).

Seismic refraction surveys were conducted at three locations in May (17 – 19) and November (6 – 8) 2013—months marking the transitional periods from dry-to-wet and wet-to-dry seasons, respectively (Proteccion Civil 2011). During the dry season, we conducted the surveys on the upper slopes. Two sites were adjacent to two separate areas that failed in 2009, and a third site was proximal to surface cracks that appeared after heavy rainfall from Tropical Depression 12E in October 2011. The first set of surveys conducted 17 – 19 May 2013 coincide with the very end of the dry season when soils would be at their driest state. The same three survey sites were revisited the first week of November 2013 coinciding with the tail-end of the rainy season. The three survey locations (*Infiernillos, Finca El Carmen, and Finca 3 Rios*) were chosen based on accessibility and proximity to slopes known to have failed in the recent past.

Infiernillos is on the eastern slope of a ridge that divides the twin edifices and is located just west of the *Infiernillos* hydrothermal vents. The site was chosen for its

unique characteristics. During heavy rainfall associated with Tropical Depression 12E in October 2011, linear cracks/sinkholes formed at the crest of the ridge upslope from the survey site. Geothermal alteration of the surficial deposits may be more pronounced at this site because of the prevalence of hot springs. Finally, slopes at higher elevation in this drainage failed in 2009, which triggered the most destructive lahar that inundated portions of Verapaz (Figure 4.2 (a,b)).

Figure 4.2 (a,b) Images showing devastation and lahar path through the town of Verapaz, El Salvador on 10 November 2009 (Photo credit: Jose Fredy Cruz Centeno).

Finca El Carmen is on the northern slopes of the younger, west edifice. Though this area did not experience as many or large slope failures as the east edifice in 2009, at least seven surficial cracks were reported in October 2011 after 12 days of heavy rain from Tropical Depression 12E. Community Civil Protection brigades reported these cracks to the UES-FMP as well as municipal governments and follow-up inspections measured and located each of these cracks using GPS. For this reason, Survey Site 2 was chosen due to public and institutional concerns about the stability of slopes in this area.

Finca 3 Rios is on the west edifice and was chosen due to its proximity to a series of landslides, many of which started after the January and February 2001 earthquakes, and were reactivated during the rains from Hurricane Ida in 2009. The survey was conducted on a ridge with major slides on both sides further up-slope.

4.3.2 Time-lapse Seismic Refraction

The seismic-refraction surveys were designed and conducted without *a priori* knowledge of the shallow geology. The intentions were to delineate the soil, rock, and

hydrological stratigraphy in the three sites that may be prone to future sliding. Time-lapse seismic refraction was performed by reoccupying the three sites at the end of the rainy season, and analyze the waveforms to show differences, if any, in arrival times between the two surveys were compared to characterize seasonal changes in the shallow soil moisture or water table depths. A waveform comparison approach allowed detection of subtle changes in both the depth to potentially perched water tables and relative soil moisture distributions within the soil profile. Without relying solely on travel-time differences from subjective identification of waveform arrival, the actual waveforms can be compared using this method, improving the detection limits of the method. To reduce ambiguity in differentiating changes in saturation from changes in lithology, both shear- and compressional-wave refraction surveys were performed.

The time-lapse waveforms should show subtle changes in both water table and saturation profiles as water content affects sound velocities. The endpoints of each line were marked with stakes and spray paint for reliable reoccupations. Survey points were established using a measuring tape, and inclination measurements were made 10-m apart using a Leupold 63335 Range finder with a built-in inclinometer. We linearly interpolated the elevation of survey points between each inclination measurement. Relative elevation was designated as zero elevation for one survey point in each line. A compass was used to measure the line orientation, and each line was followed as parallel as possible to the dip of the topography, assuming that most of the lithology variation occurred downslope.

A sledge hammer and metal plate were used to create the sound source (“shot”) for each survey. Each shot location was sampled with at least 20 hits and the results from each were added, a process referred to as stacking. The sledgehammer was equipped with an inertial switch with which to instantaneously trigger the timer in the seismograph. Waveforms were recorded using a 24-channel Geode Ultra-Light Exploration Seismograph connected to vertical geophones with a 4-Hz natural period. Sampling lengths were adjusted for each site in order to record all coherent arrivals. All waveforms were recorded at -0.2 s (before start time) with a 0.5 ms sampling interval. We chose to record waveforms prior to the start time in order to allow us to filter ambient noise from

the data without introducing edge-effect artifacts. Geophones were placed at 2 m intervals from 14 to 60 m along each survey line, as we anticipated shallow refractors for each of the survey sites. For the May (pre-rainy season) surveys, numerous redundant shot points were performed so that the stratigraphy could be determined, as the dry ground resulted in poor coupling between the steel plate and the ground. Some shot points were reoccupied in the November (post-rainy season) survey so that time-lapse comparisons could be made and additional shot locations were occupied to clarify uncertainties in the stratigraphy identified in the May surveys. The first-arrival time picks were made using only the unfiltered data from the May surveys.

Although we make use of very little of the data in this manuscript, we also performed horizontally polarized shear (*SH*) wave refraction using transversely oriented horizontal geophones in the surveys. We used a buried and inclined plate as the source (transversely oriented), which was rotated 180 degrees after 20 hits, so that each shot point possessed 40 hits, 20 in each direction. In this manner, through subtracting the positive transverse from the negative transverse shot directions, any *P* or vertically polarized shear (*SV)* waves would cancel, leaving only *SH* arrivals (Franklin 1979). Using the *SH* time-lapse aided in isolating the subsurface structure from changes in fluid saturation, and velocities from each survey were used to estimate the shear modulus for fluid substitution. These data proved too noisy for use in our primary interpretation, but were used to estimate the *SH* velocity of the surface layer at Site 3 for the fluid substitution calculation (Table 4.1).

4.4 Results

The surveys revealed different soil and moisture stratigraphies at each site. Three distinct layers (two refractors) were interpreted at one site, two layers (one refractor) at another, and one layer (no refractors) at the last site. The layers are thought to comprise a surficial dry layer of loose soil, an underlying layer of highly fractured bedrock potentially mixed with soil, and a deeper wet and/or intact-rock layer.

4.4.1 Los Infiernillos

Los Infiernillos is located to the west of a lahar path and an active hydrothermal area. The survey line transects both a crop field (downslope) and coffee plantation (upslope) with an average slope of 26º. The survey point at 60 meters was the high point and designated as the origin with a survey elevation (zero) datum (see Figure 3). The survey was oriented at N30E from the origin. Shot point locations occupied in May were conducted from the negative and positive ends of the survey line; however, many of these shots showed redundant results, so only two were required to make a complete interpretation, namely shot points at 12 and 62 m. The first-arrival time "picks" are shown in Figure 3a for these shot locations. Shots with further offsets (up to 12 m off both ends) did not show any evidence of additional deeper refractors. The upper-layer velocities were determined to be 510 and 450 m/s from the positive and negative ends of the line, respectively, with the mean upper-layer velocity being 482 m/s. The up-dip apparent velocity of the refractor was determined to be 960 m/s and the down-dip apparent velocity was 900 m/s. The apparent dip of the refractor with respect to topography is only about 1º, and depths beneath the 12 m and 62 m points were determined to be 3.4 m and 4.1 m, respectively (Figure 3b).

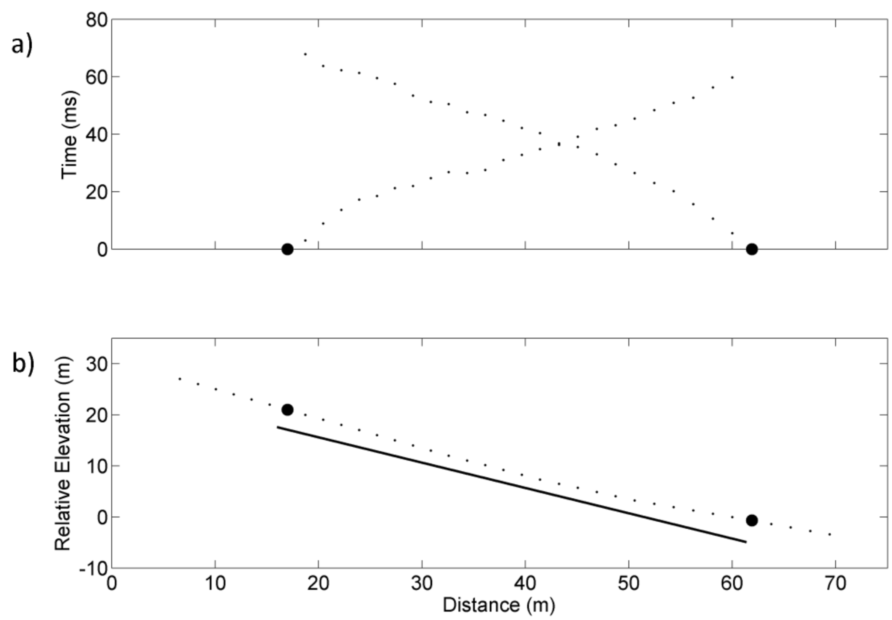

Figure 4.3 (a,b) P-wave first break arrival times (small dots) from source locations at 62 and 12 m (large dots) (a), and interpreted refractor (solid line) from sources (large dots) at

12 and 62 m off-end shot points at Los Infiernillos (b). Small dots (b) are survey points along the line and x-axis is distance along the line projected to horizontal.

The seismic refraction surveys at this site were repeated at the end of the wet season, in November, with four additional shot locations (2, 27, 43, and 60 m) which were included to increase the confidence in the dry-season (May) survey interpretation. To avoid damage to the corn crop grown during the rainy season, the geophone placement was shifted 2 m from the previous May survey, so only 23 of the 24 geophones could be used for time-lapse comparison (see Figure 4.4). Nearly identical first-break picks from both ends of this survey were identified despite the 2 m discrepancy, indicating an imperceptible change in layer properties ascertained from the seismic refraction methods. Figure 4.4 shows the time-lapse comparison from the shot point at 62 m. Neither the direct nor refracted arrivals show any significant time shifts.

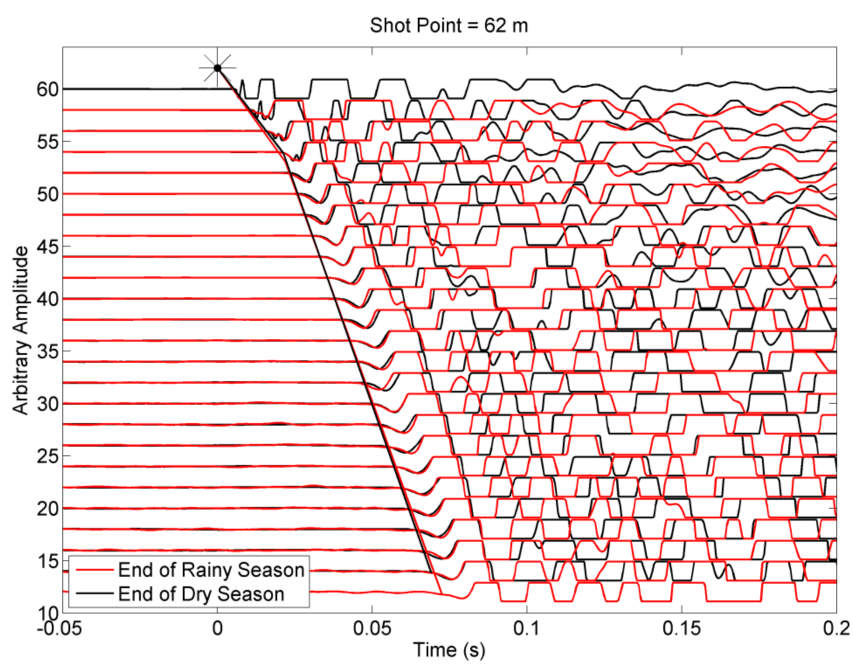

Figure 4.4 P-wave arrivals recorded from the shot point at 62 m individually normalized from each survey to demonstrate variations in first arrival waveforms from the end of the rainy season (red) to the end of the dry season (black). The survey location of each geophone is indicated on the y-axis.

4.4.2 Finca El Carmen

The seismic data were acquired within *Finca El Carmen* coffee plantation along an average slope of 23º. The survey point at 60 m was the high point of this survey and designated as the origin with an elevation (zero) datum (see Figure 4.5 (a,b)). The survey was oriented at N10E from the origin. Shot-point locations occupied in May were used from the negative end of the survey line at 4, 6, 8, 10, and 12 m, from the positive end at 62, 64, 66, and 70 m, and a single split shot was performed at 26 m. Due to the redundancy of many of the shots, only five were chosen for interpretation: 4, 12, 26, 62, and 70 m. First-break picks are shown in Figure 5a for these shot locations. No clear refracted arrivals from any of these shot locations were observed, and hence, changes in lithology cannot be interpreted from these seismic data. The constant slope shown for all of these shot locations is approximately equal to 340 m/s, which would be equivalent to the speed of sound through air (or very dry, loose soil) at ambient temperatures. Although these direct arrivals would be traveling at the same speed as the air-wave, we take these to be the velocity of the dry unconsolidated soils as observed at the surface.

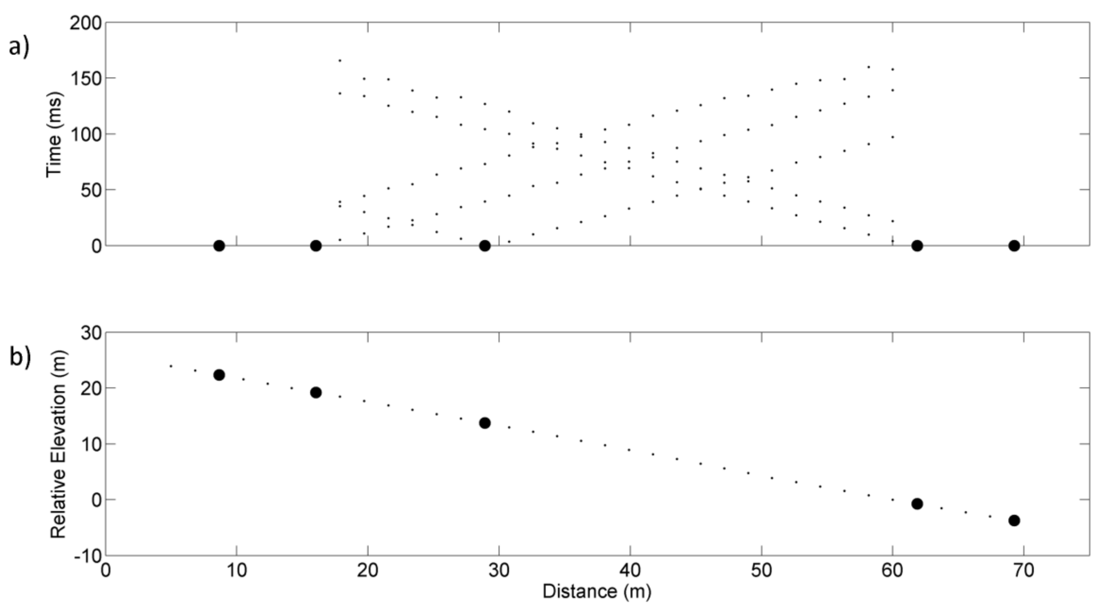

Figure 4.5 (a,b) A single layer with no refractor is observed from both directions at all five shot points (a) with a relative elevation profile (b) along the survey line.

While the data does not allow delineation of the geology at this site, the measured velocities can be used in theoretical estimates of the minimum depth to the top of a potential refractors. Assuming that a minimum of three geophones recording refracted arrivals from the most-offset shot point (shot = 4 m) are needed, the minimum depth to a horizontal refractor can be calculated using the measured velocities and the time-intercept method (Staub 1969). Figure 4.6 shows a theoretical estimate of the maximum resolvable depth to a hypothetical refractor with several reasonable refractor velocities, with the top of the refractor exceeding 17 and 19 m for refractor velocities of 1000 and 1500 m/s, respectively. In the case of this site, the repeat survey would only reveal changes in soil saturation or the potential encroachment of water within the resolvable depth of the survey geometry.

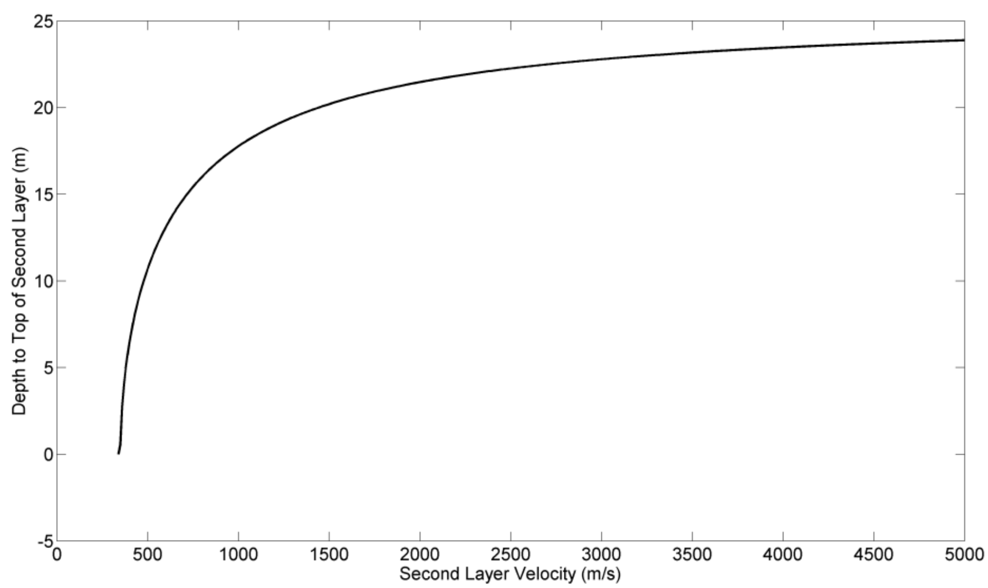

Figure 4.6 Hypothetical refractor depths resolved with reasonable refractor velocities in volcanic terrain. Refractors deeper than about 20 m cannot be imaged.

The *Finca El Carmen* survey was repeated in November at shot points 4, 12, 62, and 70 m. Additional split shots at 29 and 45 m were used to increase confidence due to the lack of clear refractors in the May survey. Additional shots at off-end locations of -6 and 80 m were performed to increase the survey penetration depths. Neither the split shots nor the further off-end shots illuminated any refractor. Figures 7a and 7b show the time-lapse refraction waveforms overlain for shot locations 12 and 62 m, respectively.

Due to inconsistent low-frequency noise encountered during the May and November surveys, we performed a fourth-order high-pass Butterworth filter above 200 Hz. Neither shot location reveals significant differences in the first-break pick times, but the November survey shows a linearly increasing time delay that is offset in comparison to the May survey. We interpret this as a slight decrease in the shallow soil velocity, but cannot confidently differentiate this change between subtle saturation differences or possibly slight errors in geophone or shot relocations in the November survey. The 12 m off-end shot reveals a ~1% velocity decrease from 350 m/s to 340 m/s and the 62 m shot from 353 to 347 m/s from May to November, although minor differences in first-break interpretations may eliminate this velocity reduction entirely, so this difference should not be considered significant. The *Finca El Carmen* site reveals survey repeatability, but no measurable variations in water table depth nor soil saturation were revealed with the seismic data.

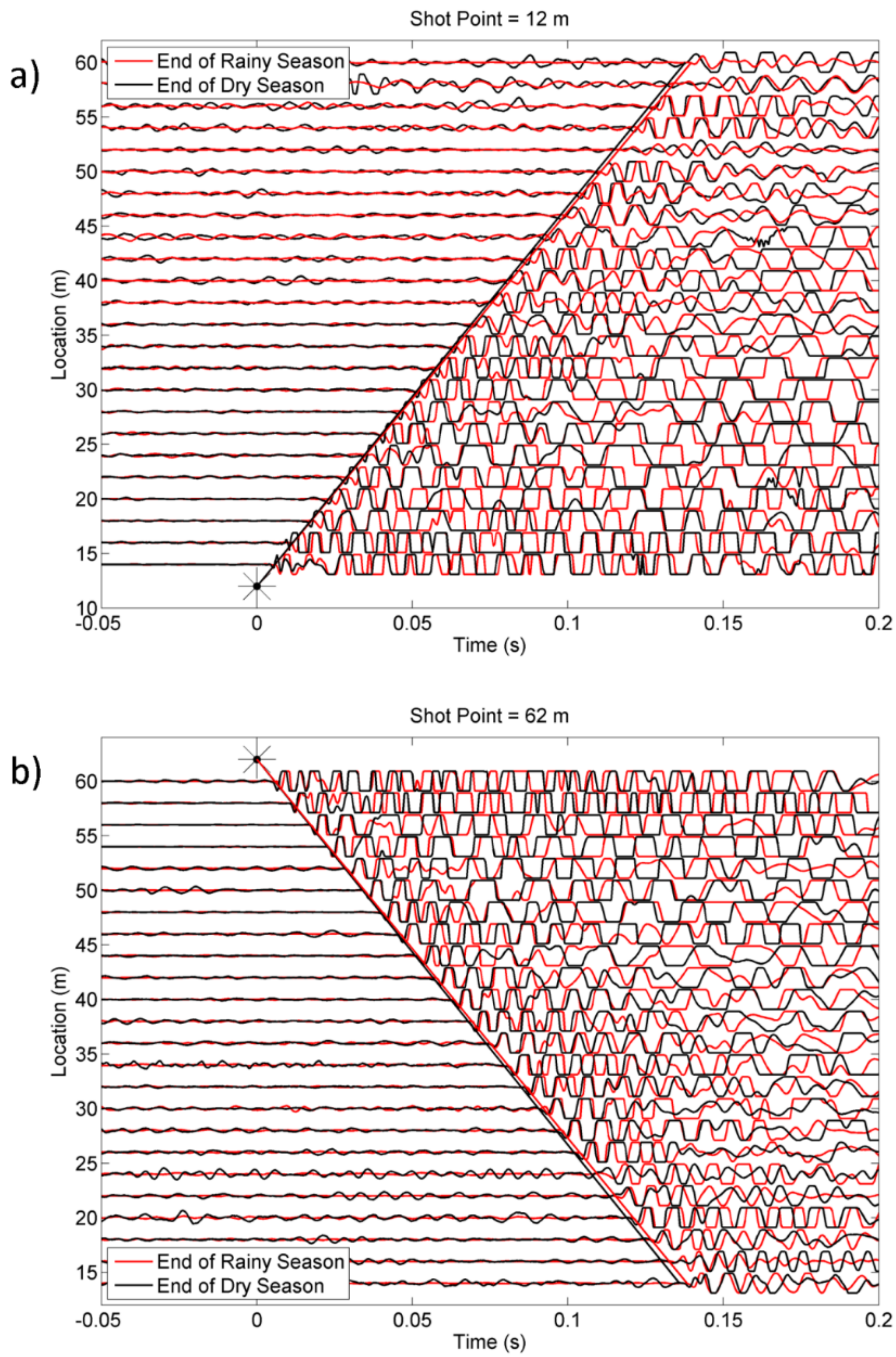

Figure 4.7 (a,b) First breaks in both directions were individually normalized from each survey to demonstrate variations in first arrival waveforms from the end of the rainy season (red) to the end of the dry season (black). The survey location of each geophone is indicated on the y-axis. The arrival times reveal little change between seasons but show survey repeatability.

4.4.3 Finca 3 Rios

The seismic data were acquired within a portion of the *Finca 3 Rios* with an average slope of 27º. Contrary to the other two survey sites, the survey point at 60 meters was established at the topographically higher end of the survey line, but was still defined at a relative elevation of zero (see Figure 4.8). The survey was oriented at N80E from the origin (zero-meters distant). Shot point locations occupied in May were conducted from the negative end of the survey line at 0, 2, 4, 6, 8, 10, and 12 m, from the positive end at 62, 64, 66, 68, and 70 m, and two split shots were performed at 28 and 48 m. Figure 4.8a shows the first-break picks selected at shot locations of 0, 12, 28, 48, 62, and 70 m. This survey revealed consistent direct arrivals at velocities of 410 and 420 m/s from the 12 and 62 meter shot points, respectively, a clear primary refractor from both ends of the survey and the split shots. A possible second refractor was imaged with data gathered at shot points taken far from the positive end of the survey line. A dip in the primary refractor is also evident around a position of 42 m. Depths perpendicular to the slopes beneath shot points 12 and 62 meters were calculated to be 7 and 3 meters, respectively, using the conventional time-intercept method. Figure 4.8b shows the simple interpretation of this site.

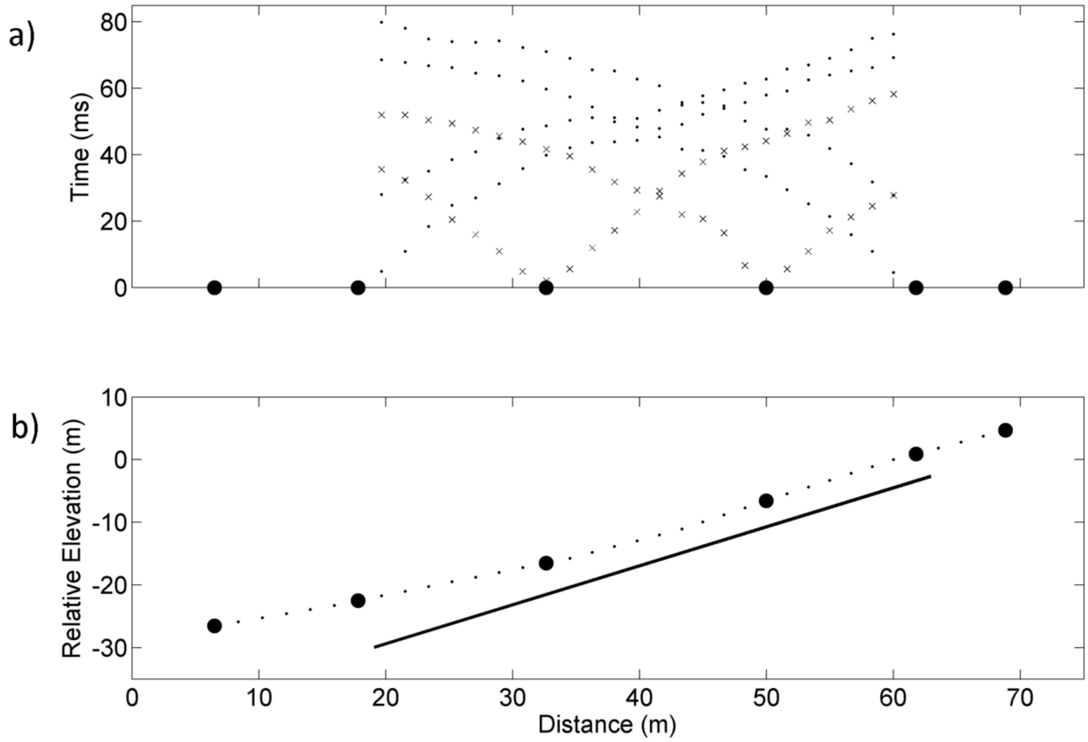

Figure 4.8 (a,b) P-wave first break arrival times (small dots = forward and reverse; small X's = split shots) from source locations at 0, 12, 28, 48, 62, and 70 m (large dots; a and b), and interpreted refractor (solid line) from sources at Los Infiernillos (b). Small dots (b) are survey points along the line and x-axis is distance along the line projected to horizontal. The solid line indicating the refractor shows the shallow layer thickening downslope.

The *Finca 3 Rios* survey was repeated in November at shot points 0, 4, 12, 62, 66, and 70 m. Only the closest, on-end shot points at 12 and 62 m were used for the time-lapse interpretation, shown in Figure 4.9. First-break lines were drawn independently on each stage of the survey to highlight lithology changes, which ignored small-scale variability in the refractor and focused on the average slope shown by the first-breaks. Both ends show distinctly different *P* wave velocities between the May and November surveys for the direct waves through the upper layer, with the November survey displaying a lower velocity than the corresponding May survey. The two primary refractor slopes are essentially parallel indicating that although the picks are shifted as a result of a velocity change in the upper layer, the velocity of the refractor has not changed substantially. The shot point at 62 m also shows a slight difference in slope between

layers for the second refractor (third layer), but the signal to noise ratio deteriorated significantly for these offsets, which suggests that interpreting this minimal change in velocity may not be appropriate due to data quality.

The arrivals of the direct wave through the upper layer show a slope in first-breaks of slower velocity in November than May as recorded from both ends of the line. Namely, the 12 m shot shows a first layer decrease in velocity from 420 to 360 m/s (14% reduction), and the 62 m shot shows a first layer decrease from 420 to 380 m/s (10% reduction). This change in velocity is significant and cannot be attributed to survey uncertainty since this trend is apparent from both ends of the line. The refractor (second layer) shows less variation in velocity between phases, namely a 10% decrease and 2% increase respectively from each end. Note that the velocity values from the May survey used to determine the general stratigraphy were determined mathematically using least-squares regression and differ slightly from those interpreted in the time-lapse comparison. Although we restrict our interpretation of the dispersed wave-train following the first-break to a qualitative interpretation, the time delay shown by the first trough visually confirms an apparent phase shift (see Figure 4.9).

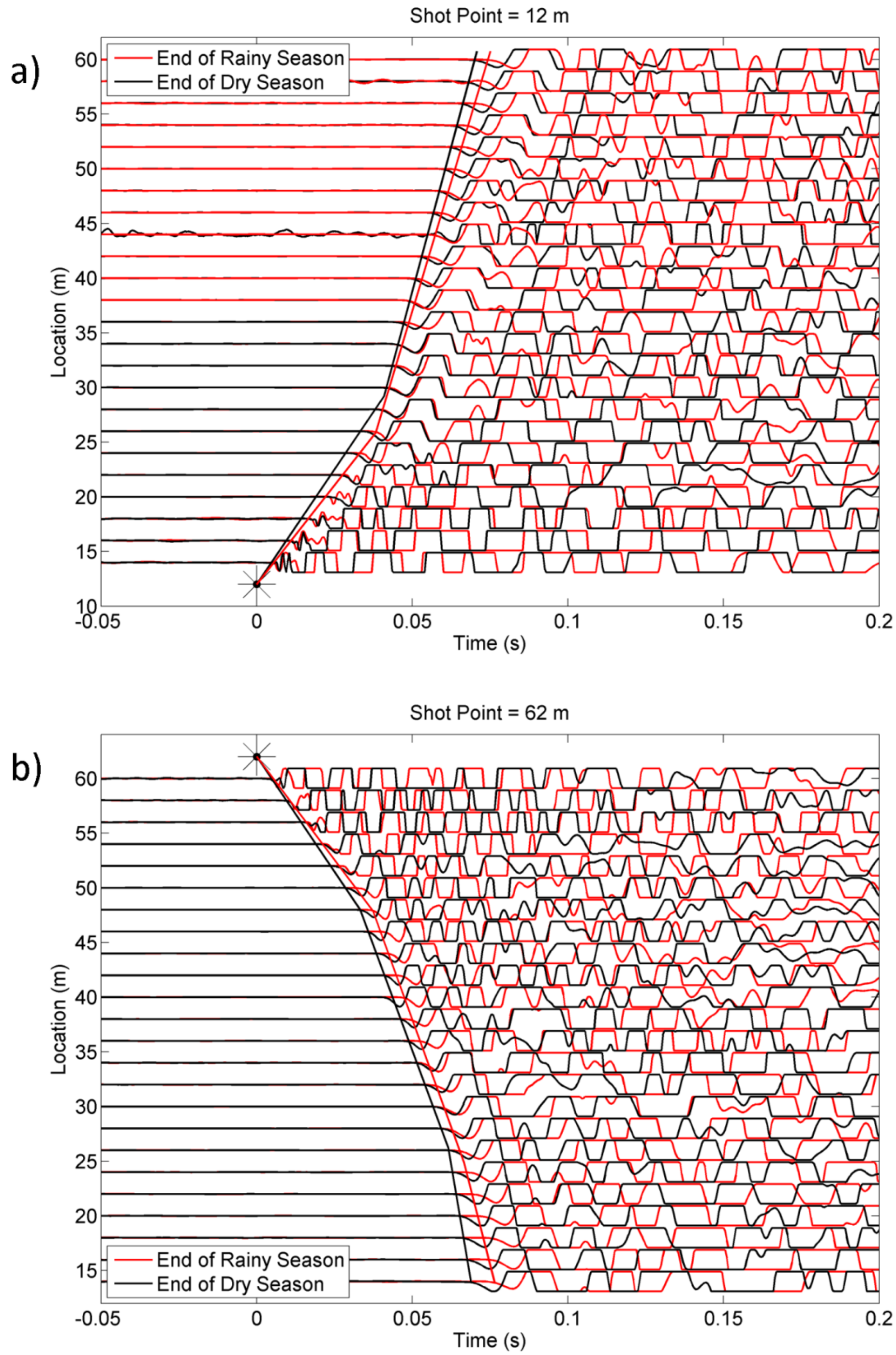

Figure 4.9 (a,b) The first breaks in both directions were individually normalized from each survey to demonstrate variations in first arrival waveforms from the end of the rainy season (red) to the end of the dry season (black). The survey location of each geophone is indicated on the y-axis. First breaks in both directions reveal a lower velocity only in the first layer in November when compared to May, while the second and third layers are nearly equivalent velocities but show accumulated delay from the slower first layer.

In order to fully utilize the data to interpret water saturation changes within the surface layer at this site, Gassmann fluid substitution was performed using the refraction interpretation (Bachrach and Nur 1998; Han and Batzle 2004). Gassmann substitution requires knowledge of the shear modulus, so the results from the *SH* survey also performed at this site are used for this calculation. These data required low-pass filtering below 50 Hz to eliminate *P*-wave arrivals and noise, but allowed a surface layer *SH* velocity to be determined from the shots at 12 and 62 meters. Opposing transverse shot directions clearly showed opposite polarities, and *SH* velocities determined were 165 and 170 m/s from 12 and 62 meter shot locations, respectively. First, a bulk density of the andisol of 1280 kg/m^3 is assumed (Lal 2006), which corresponds to water saturation of 80%, porosity of 60%, and grain density of 2000 kg/m^3. The average *SH* velocity of 168 m/s and bulk density were used to solve for the shear modulus, determined to be 36 MPa. Likewise, using the shear modulus, the bulk modulus of the saturated medium (in November) was determined to be 128 MPa. Additional input parameters for these calculations are listed in Table 4.1.

Table 4.1 Assumed rock properties, measured seismic velocities, and calculated parameters used in fluid substitution.

Measured Values		
	May	November
V_P (m/s, average)	421	371
V_{SH} (m/s, average)	---	168
ρ_{air} (kg/m^3)	1.18	1.18
Estimated Values		
	May	November
Saturation	---	0.80
ρ_{grain} (kg/m^3)	2000	2000
ρ_{water} (kg/m^3)	1000	1000
ρ_{bulk} (kg/m^3)	---	1280
φ	0.60	0.60
V_P (m/s, in air)	330	330
K_{grain} (GPa)	20.0	20.0
K_{water} (GPa)	2.15	2.15
Calculated Values		
	May	November
K_{air} (kPa)	128	128
$\mu_{saturated}$ (MPa)	36.1	36.1
$K_{saturated}$ (MPa)	127	128
Saturation	0.32	---
V_{SH} (m/s)	191	---

Using equation 2 from *Knight et al.* [1998], the bulk modulus of the initial fluid-air mixture was determined: air and water bulk moduli being 128 kPa and 2.15 GPa, respectively. The bulk modulus of the initial fluid was 641 kPa, and substituting different mixtures back into equation 2 [*Knight et al.* 1998], bulk moduli for different saturations were calculated. Using Gassmann substitution (Han and Batzle 2004), *P* and *SH* velocities for water saturations were determined to range from 0 to 1.0, namely from air saturated pores to fully water saturated pores (Figure 4.10).

Saturation is almost certainly higher following the rainy season in November than it was at the end of the six-month dry season in May, so *P* wave velocities are plotted

from May to determine the lower saturation velocity intersection with the predicted *P* wave velocity. The intersection yields an estimate of the May water saturation at 32%, which is half of the water content determined from the November survey. Varying the starting assumed saturation from 0.4 to 0.97 yields saturation increases from May to November of 39% to 58%, indicating that the saturation increase is relatively insensitive to the starting value of saturation (using the November survey as our starting saturation). Only when the starting value of saturation is near 98% do minor changes in the saturation value then heavily affect the P wave velocity (i.e. sharp increase; Figure 4.10).

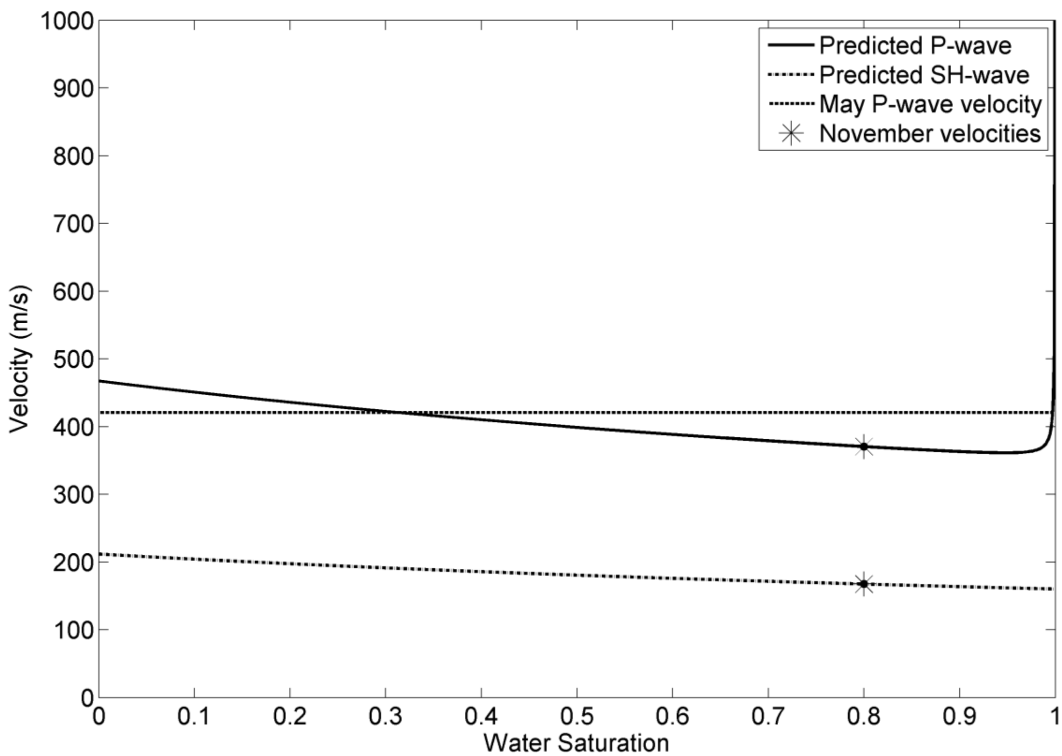

Figure 4.10 Predicted and measured *P* and *SH* wave velocities and layer saturation percentages for both May and November surveys.

4.5 Discussion

Characterizing slope lithology and the identification of perched water tables were primary goals of this study following Smith's et al. (2015) study indicating that groundwater table depth was a critical factor leading to slope instability. Saturation

differences due to accumulated rainfall between the dry and wet seasons might help us understand whether water table depths varied seasonally and thus might contribute to shallow landslides toward the end of the rainy season and during intense tropical rainfall events.

Detecting perched water tables was not possible—not necessarily due to the methods used, but because of other potential factors. This field work was conducted after two consecutive comparatively light rainfall years. As seen in Table 4.2, 2012 and 2013 were both relatively dry years. One explanation is that saturated layers could not be imaged because not enough precipitation had accumulated throughout the rainy season to fully saturate soils above impermeable layers. Precipitation data were obtained from two sources, both showing less-than-average rainfall amounts for 2012 and 2013. Data from the aWhere Inc. online platform are compiled from a global network of weather stations in conjunction with satellite data to provide weather information over 9 by 9 km grid cells. "For rainfall, aWhere delivers a new blended rainfall product from Colorado State University based on a constellation of 8 polar-orbiting satellites" (aWhere-Inc. 2014). In situ precipitation data were obtained from both SNET and UES-FMP weather stations. This data set shows significant time gaps due to the remote location and inaccessibility of SNET's weather station; however, the 2012 and 2013 data from the UES-FMP station is complete. There are gaps in the data from May – July 2007, but even so, accumulations reach 1671 mm of rainfall. Though the aWhere organization does not specify how rainfall is calculated with satellite instrumentation, when compared with in-situ weather stations at San Vicente volcano, the program likely underestimates the true value of accumulated rainfall, as can be seen from comparing total amounts in Tables 4.2.

Table 4.2 Precipitation data from aWhere Inc. platform (aWhere Inc. 2014) and SNET, UES-FMP weather stations.

Precipitation: Accumulated Rainfall (May – November)		
Year	**Rainfall (mm) SNET and UES-FMP**	**Rainfall (mm) aWhere Inc.**
2004	1955	NA
2005	No Data	NA
2006	2044	NA
2007	1671*	NA
2008	2276	1195
2009	2303	1021
2010	Missing Data	1526
2011	Missing Data	1175
2012	Missing Data	800
2013	1401 (March – November)	922

Due to the unreliable operation and data acquisition of the SNET weather station, a new network of Davis weather stations was deployed by the Center for Disaster Protection (CEPRODE) in 2012. Six stations now provide a more complete archive of weather data for the entire northern flank of San Vicente volcano.

Not only was 2013 a relatively dry year, the tail end of the rainy season was noticeably drier than average years. Only 220 mm of rain fell during the month of October, which is less than half of the monthly average, and during the two weeks before the November 2013 fieldwork, only 30 mm of rain was observed. Only 0.6 mm of rain was measured the week before the field work. Even though the rainfall in 2013 was well below average, it was sufficient to result in an increase in the water table height of a few meters. Rising water tables were not observed, however, so either the water table is deeper than anticipated or the permeability of these shallow volcanic deposits allow the infiltration to flow downslope without significant buildup.

Although the rainy season was very moderate in 2013 (and 2012), data show that the soils have a high capacity to absorb and retain moisture. Andisols are formed primarily from volcanic ash and characteristically are able to retain moisture over long periods of time (Shoji and Dahlgren 1994). During intense rainfall events, andisols can become saturated. After a high rainfall year in 2009, finally ending with the Hurricane Ida event (355 mm of rain over a five-hour period), soils were unable to drain or absorb

additional precipitation, causing the shallow landslides (Smith et al., 2015). Results confirm conclusions made by Smith et al. (2015) that slopes on San Vicente are highly permeable, as no significant saturation changes were seen between the end of the dry and wet seasons. Smith et al. (2015) also concluded that slope geometry proved a critical factor in modeled landslide generation. Though field sites were chosen due to their proximal location to past landslides, there is no indication that slope geometry at survey sites was (or was not) conducive to slope stability.

Another reason why saturated layers were not imaged could be that subsurface conditions at each of the three sites were not conducive to establishing perched water tables. If an impermeable layer was absent at the selected site, then capturing saturated layers would be difficult or impossible. Sites were selected due to their proximity of slopes that had recently failed or were suspected weak slopes; however, subsurface conditions could vary widely over short distances. Perhaps the slopes that failed in 2009 exhibit hypothesized conditions, and nearby slopes that were occupied for this experiment drain more efficiently, and hence, did not fail in 2009.

The repeatability of the survey results bolster confidence in the methods chosen for this work, but a consideration of other factors might render more robust results in the future. Returning to the three survey sites after a normal (or extraordinary) rainy season or after a significant tropical rainfall event might show saturated layers that were not possible to image in 2013. Occupying completely new sites might broaden our understanding of slope and subsurface characteristics and potentially identify new areas where impermeable or saturated layers can be identified. Finally, combining the time-lapse seismic refraction methods with other geophysical methods like resistivity surveys might help constrain the interpretation of subsurface saturation characteristics.

4.6 Conclusions

Though this investigation did not identify a definitive water table depth nor saturated layers at the three sites on San Vicente volcano, the time-lapse seismic refraction methods used showed high repeatability and were able to image distinct stratigraphic layers at sites where layers existed. Given normal wet-season conditions, a

broader selection of survey sites, and/or a campaign combined with other geophysical methods, future campaign results might indicate the existence of perched aquifers or other specific conditions that contribute to unstable slopes in volcanic terrains.

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