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Uniting remote sensing observations and human experiences to understand recent eruptive activity of Volcán de Fuego, Guatemala

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Todo se oscureció

uniting remote sensing observations and human experiences to understand recent eruptive activity of Volcán de Fuego, Guatemala

By

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ABSTRACT

This thesis presents an interdisciplinary case study of the active Volcán de Fuego in southern Guatemala to examine: (1) the physical behaviours and volcanic hazards that characterize eruptions occurring in recent years, and (2) the factors that influence local residents' decision to evacuate from these eruptions. The thesis presents different answers to these issues depending on the data sources studied: satellite observations, geophysical and gas timeseries, and observations of and interviews with local residents and authorities. The thesis begins by presenting Fuego as an ideal subject for an interdisciplinary volcanology PhD, and establishes the philosophical positions and methodological approaches that were necessary to consider in order to undertake both physical and social science research within this PhD. The first results of this thesis are satellite observations of Fuego's activity between January 2015 and June 2018. These observations, supplemented by other data, identify a new eruptive regime characterized by frequent explosive eruptions ("paroxysms") consistently preceded by lava flow effusion. Thresholds for determining eruption are debated. Physical results are juxtaposed with qualitative narratives of previous eruptions of Fuego and evacuations of communities as told by both authorities and local residents of rural communities around the volcano. These narratives reveal that an eruption at Fuego is not a consistent phenomenon, but is experienced differently by different observers based on their previous experiences, knowledge, resources, and priorities. Finally, quantitative and qualitative data are integrated through analysis of timeframes of eruption and response for several recent eruptions. Quantitative timescales and their qualitative counterpart, timelines, provide detailed chronologies of times and uncertainties involved in forecasting eruptions of Fuego and of deciding, warning, responding to, and evacuating from eruption. Ultimately, this thesis concludes that the lives of local residents cannot be reliably protected from hazards of Fuego without integration of the monitoring and risk mitigation efforts of INSIVUMEH and CONRED. This integration mirrors that of physical and social drivers of volcanic risk explored within this work. This thesis demonstrates the value of integrating physical and social research methods in a single interdisciplinary project, and contributes to volcanological literature with findings that volcanic risk is both spatially and temporally variable around a single volcano.

DEDICATION AND ACKNOWLEDGEMENTS

For anyone who dislikes cheese, I encourage you to skip to the Chapter 1. Like the finest Camembert, this dedication is rich, melting, a bit nutty, and occasionally funky. If you are here hoping to find yourself, welcome, and please read on.

I am grateful to the University of Bristol's School of Earth Sciences community that has provided a warm, nourishing, and fertile working environment since 2016. To my office friends in G9, for their companionship: Katharine, George P, Qian, Tom. The WMB shitposting group has provided laughs and solidarity through many a frustrating week - thank you to Tom, Ellen, Anna, Emma, Gareth, Rhys, Suresh, and Melisa. Thanks to the extended volcanology group, present and past: Frances, Jen, Damaris, Hannah, Josh; Ryan, Ery, Keri, Nicky, Nick, and Claudio. Thanks also to Kathy Cashman and Jo Gottsmann: our discussion in my third-year APM invigorated this project. A special thanks to particular friends who have been so influential: to Bob, whose generosity and sense of humour are second to none, and whose intelligence is such that all company leave feeling brighter - thank you for innumerable good conversations. To Benedict, a true iconoclast in tie-dye. To my desk buddy Fee, who is the cat's pyjamas - I hope to take you in my next office. To George, a first-rate academic, musician, and friend, who has been there since the beginning. And to Jacob, a hilarious and very kind friend whose compassion has seen me through many a crisis. I'm lucky to be part of such a community.

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AUTHOR'S DECLARATION

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: .... DATE: ....

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List of Acronyms

ALFA INSIVUMEH’s Communication Centre for Information Dissemination.

COCODE Consejos Comunitarios de Desarrollo - *(Community Development Council)*.

CODRED Coordinadora Departamental para la Reducción de Desastres - *Departmental Coordinator for Disaster Reduction*.

COLRED Coordinadora Local para la Reducción de Desastres - *Local Coordinator for Disaster Reduction*.

COMRED Coordinadora Municipal para la Reducción de Desastres - *(Municipal Coordinator for Disaster Reduction)*.

CONRED Coordinadora Nacional para la Reducción de Desastres - *(National Coordinator for Disaster Reduction)*.

CORRED Coordinadora Regional para la Reducción de Desastres - *Regional Coordinator for Disaster Reduction*.

CTE Centro de Transmisión de Emergencias - *Centre of Transmission of Emergencies*.

DGAC Dirección General de Aeronautica Civil - *Civil Aviation Authority*.

INSIVUMEH Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología - *(National Institute of Seismology, Volcanology, Meteorology and Hydrology)*.

MIROVA Middle InfraRed Observations of Volcanic Activity.

OVFGO1 Observatorio del Volcán de Fuego Uno - *(Observatory One of Fuego Volcano)*.

OVFGO2 Observatorio del Volcán de Fuego Dos - *(Observatory Two of Fuego Volcano)*.

RSAM Real-time seismic amplitude measurement.

SE-CONRED Secretaria Ejecutiva de CONRED - *(Executive Secretariat of CONRED)*.

UPV Unidad de Prevención en Volcanes - *(Volcano Prevention Unit)*.

List of Spanish terms

arena "sand", or relatively coarse tephra fall from Fuego. Typically described as dark in colour and highly abrasive and associated with large-magnitude eruptive events.

barranca A steep-sided drainage ravine.

ceniza "ash", or relatively fine tephra fall from Fuego. Can be dark or light in colour, and typically associated with smaller eruptive events than arena.

Ciudad Vieja literally "Old City", Ciudad Vieja is a town in the Guatemalan department of Sacatepéquez. Formerly known as "Santiago de los Caballeros de Guatemala", it was the colonial capital of Guatemala until its destruction by lahars from Volcán de Agua in 1541.

finca An estate. Around Volcán de Fuego, fincas generally comprise of a central building surrounded by land that is either used for leisure or cultivated for food production, typically coffee.

fíjese que The ultimate get-out clause. Use before any excuse, however lame, to absolve yourself of responsibility.

hijo de la gran puta A casual Guatemalan slur used to express disbelief or surprise.

humazón A cloud of dark smoke. A term used by local residents at Volcán de Fuego to describe pyroclastic flows.

necio Foolish, naughty, or featherbrained. Not usually used to refer to a volcano or its activity, as I mistakenly did for a month during fieldwork in 2019.

piedra literally, "stone". A local non-technical term for lapilli, "piedra" describes very coarse tephra fall from Fuego. Typically described as dark in colour and highly abrasive, and associated with large-magnitude eruptive events.

Todo se oscureció "Everything went dark". A phrase commonly used by local residents around Volcán de Fuego to describe the eruptions of 1966, October 1974, and 3rd June 2018.

Un paso adelante "A step forward". A phrase used in Latin American Spanish to describe progress.

vigía "watchman". Describes the network of volunteer observers drawn from communities around Volcán Tungurahua in Ecuador.

volcán volcano.

Volcán de Agua literally, "volcano of water". Agua is a historically active stratovolcano 10km east of Volcán de Fuego. Its name comes from its association with lahars or volcanic mudflows that destroyed the colonial capital of Ciudad Vieja in 1541.

Volcán de Fuego Volcano of Fire.

FIGURE 1. A visualization of my PhD progress from beginning in September 2016 to submission in summer of 2020. Artwork my own.

CHAPTER 1

INTRODUCTION

The view from the terraces of Volcán Acatenango is spectacular. On a clear day one can see the perfect cone of Volcán de Agua with the cities of Alotenango and Ciudad Vieja nestled in its folds. Also visible is the full anatomy, from foot to summit, of Acatenango's southernmost sibling, Volcán de Fuego. Fuego is the currently active eruptive centre of the Fuego-Acatenango Massif and is a dramatic presence beside the plains of southern Guatemala. By tracing a finger from the summit down one of Fuego's barrancas (ravines), the observer arrives at one of the many communities at Fuego's base. This direct line between community and volcano comes alive when an explosion from one of Fuego's summit vents ejects metre-diameter ballistics that descend toward the barrancas.

Seen from below, the view of Fuego is more impressive still. From km 91 of road RN-14, the eroded upper scarps of Barranca Las Lajas record the tragedy of 3rd June 2018, when a paroxysm buried the community of San Miguel Los Lotes under pyroclastic flows. While Los Lotes is the most recent reminder of Fuego's power to devastate, other monuments record a long history of destruction. A low wall claimed by vines in Panimaché Dos marks a chapel destroyed in the October 1974 eruption. The mud-filled toilets of a Scout encampment on the Ceniza river show the destructive power of Fuego's seasonal lahars. Swollen by pyroclastic material from recent eruptive activity, these lahars now threaten larger communities downstream. Seen in this way, the myriad hazards associated with Fuego's eruptive activity are inextricably tied to the activities of people that live around the volcano.

FIGURE 1.1. Volcán de Fuego's summit, Barranca Honda, and communities of La Reina, Don Pancho, and La Trinidad visible from the terraces near the summit of Volcán Acatenango. Picture taken 23/03/2019.

1.1 Thesis Rationale

Disasters worldwide appear to be escalating. Rarely a week passes without media reports of a hurricane, earthquake, or flood that has devastated a population. This impression is validated by comprehensive assessments of risk: the frequency and size of losses associated with natural hazards are indeed increasing globally [UNISDR, 2011], and forecasts of anthropogenic climate change and their effects have manifested even earlier than predicted [UNDRR, 2019]. The acceleration of losses associated with natural hazards is due to the increase of populations in environments exposed to those hazards. For example, in 2015 approximately 1 billion people worldwide lived within 100 km of a Holocene volcano; with "human concentrations in this zone increasing since 1975 above the global population growth rate" [Freire et al., 2019]. While it seems obvious that more people living in a hazard-prone environment will result in more people potentially exposed to such hazards, the interaction between people and their environment is not so linear. Instead, this interaction is an intricate web of factors and feedback loops with interconnected consequences that are difficult, if not impossible, to forecast. Therefore, mitigating risk associated with natural hazards requires a much more sophisticated response than, "Why don't the people simply move away from the hazard?". As the worldwide population continues to grow and impacts of anthropogenic climate change accelerate, natural hazard researchers need to engage with both the natural environment and the humanity it sustains. Truly, “at no point in human history have we faced such an array of both familiar and unfamiliar risks, interacting in a hyper-connected, rapidly changing world” [UNDRR, 2019].

Volcanoes are a natural hazard that frequently threaten lives and livelihoods [Barclay et al., 2019]. However, the timescales over which these hazards occur, as well as their magnitude and evolution, are all matters of great uncertainty. The mercurial nature of volcanic systems means that scientists charged with monitoring them face challenges in two areas: the physical and the social. Forecasting eruption is an ultimate goal of volcanology [Sparks, 2003], but the complex physical processes that govern volcanoes make that goal elusive. Additionally, scientists must communicate their knowledge of volcanic activity and hazards to non-scientific stakeholders who frequently have a different view of the risk [Donovan and Oppenheimer, 2014]. Scientists may also be obliged to communicate their knowledge outside of their sphere into a wider social and political context. Volcanic risk communication is most effective when it involves multiple stakeholders and encourages dialogue between them; in this environment, hazard specialists such as scientists assume a ’participatory’, rather than a ’delivery’, role. [Barclay et al., 2008]. Consequently, information on volcanic activity travelling outside of the scientific sphere may be newly vulnerable to multiple (and mis-) interpretations [Donovan, 2019]. In this way, the scientist monitoring an active volcano occupies an uneasy position in the intersection between eruptive and human activity in an increasingly complex and interconnected world.

Uncertainty and accountability are inherent not only to scientific but also to decision-making roles at a volcano. Decision-makers may face uncertainties in the quality and range of volcanic hazard information received, and their role is made more difficult if good communication methods are not developed with scientists in advance of a crisis [Barclay et al., 2008]. Decision-makers may also mistrust scientists because of their inability to reduce uncertainty [Haynes et al., 2008]. Furthermore, decision-makers, whose role inherently prioritizes risk from natural hazards, often have to communicate their decisions to populations who consider such risks among many other threats to their lives. Consequently, decisions taken to reduce risk from natural hazards may appear to these populations to decrease their security overall [Christie et al., 2015].

The majority of active and populated volcanoes accommodate the stakeholder roles described above – scientific, decision-making – as well as the roles played by local residents. Efforts to reduce risk associated with an active and populated volcano are more likely to be successful when they include knowledge of both the volcano’s physical behaviour and the human environment (including the social, cultural, economic, and political context) in which this behaviour occurs. “Advances require interdisciplinary efforts drawing on physical, social and decision science methods ... to be successful, risk reduction measures rely on the integration of these approaches” [Hicks, 2012]. However, integrating these approaches is not trivial. Indeed, developing interdisciplinary methods to effectively reduce volcanic risk is a primary challenge of modern volcanology.

1.1.1 Bridging the gap: integrating hazard assessment and risk mitigation

Many monitoring efforts at active volcanoes are based on identifying consistent increases in geophysical signals that may aid forecasting of eruptive activity. However, improved ability to forecast an eruption does not also promise that the negative impacts of the eruption can be reduced. At first this may seem obvious – but why? If we imagine a relatively predictable system, where each eruption of a 'well-behaved' volcano followed a similar trajectory to climax, we might also imagine the ways volcanic risk were affected. A predictable volcano would allow greater accuracy of early warning systems. This may consequently increase locals' trust in these systems, and encourage intention to comply evacuation orders. Such orders might be more easily given, as a more predictable system might allay institutions' fears of "crying wolf" that encourages a culture of caution regarding costly risk reduction measures like evacuation [Doyle et al., 2014]. A more predictable system, therefore, would seem likely to produce a reduction in volcanic risk. However, multiple examples show us where reality diverges from theory. Even with a relatively well-understood volcano, or with sophisticated tools to trace its behaviour, translating good understanding and forecasting ability into effective risk reduction is non-trivial. The infamous example of Guadeloupe in 1976 provides an early example of how even with clear volcanic signals deviating from a known baseline, political and social divides complicated decisions of how to respond [Feuillard et al., 1983]. Meanwhile, the December 2019 eruption of White Island that killed nine people shows that even today, with comprehensive monitoring and education, volcanic risk is often a secondary consideration after other priorities are evaluated [Benton et al., 2019].

Figure 1.2 shows a volcanic risk management framework from the MIA-VITA (MItigate and Assess risk from Volcanic Impact on Terrain and human Activities) project (see `https://cordis.europa.eu/project/id/211393/reporting`). This project developed tools to mitigate risks from various hazards of active volcanoes. MIA-VITA maintained that efficient volcanic risk management requires an integrated risk management methodology to be available for local authorities and scientists. The methodology proposed would provide simultaneous advances in prevention, crisis management, and recovery [Thierry, 2014]. In order to achieve these advances, MIA-VITA developed an integrated framework of different areas of knowledge and transfers between them. I have adapted this figure to locate my contributions to knowledge within this thesis, and to order these contributions according to each of my nine research objectives (see Section 1.2.3).

Some of the challenge of successfully integrating volcanic hazard assessment with risk mitigation is due to a country's development level [Donovan, 2019]. In the most recent (2019) Human Development Index (HDI), developed by the UN as "a summary measure of average achievement in key dimensions of human development", Guatemala scored 0.663 [UN, 2021]. This represents "Medium Human Development", indicating that Guatemala has made limited progress towards key dimensions of human development. Prioritizing volcano monitoring when

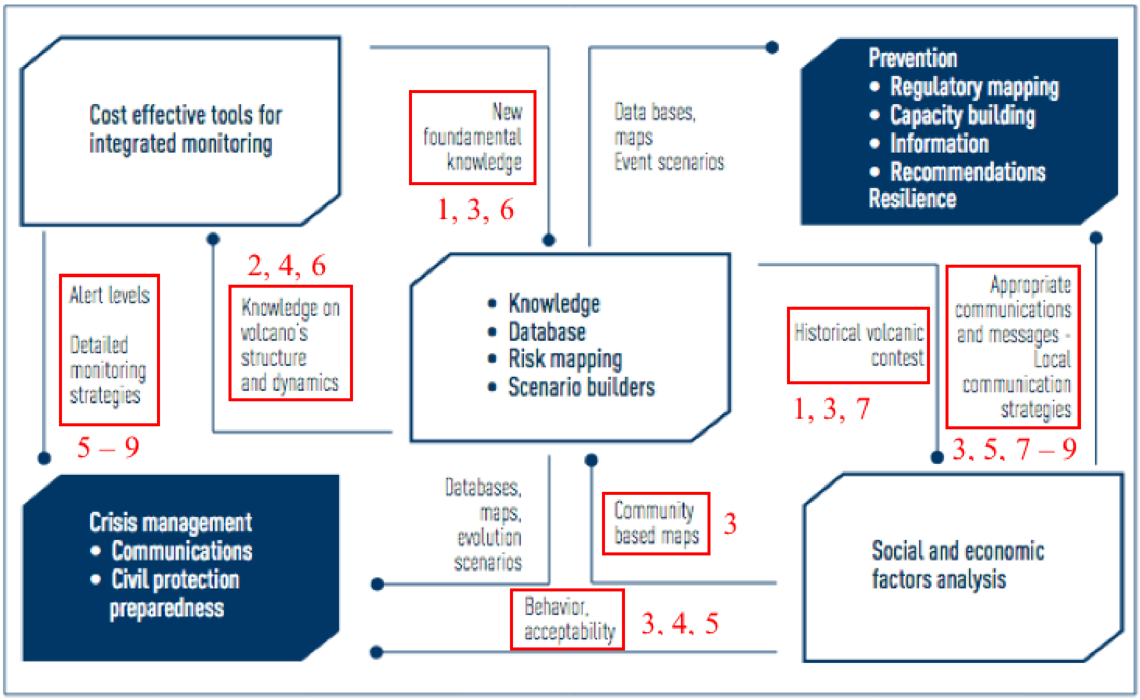

FIGURE 1.2. Methodological framework with related information flows for management of volcanic threat, from Handbook for Volcanic Risk Management created by MIAVITA project. From Bignami et al. [2013] via Delos Reyes [2019]. Red annotations are mine: boxes indicate areas in which this thesis has contributed knowledge, numbers indicate thesis goal that corresponds to this contribution.

more basic needs are not met is very difficult [Tilling, 2008]. However, 95% of Guatemala's population lives within 100 km of an active volcano [Loughlin et al., 2015a]. In addition, all of Guatemala's Holocene volcanoes have >100,000 residents of rural communities living within 30 km of their summit [Loughlin et al., 2015b]. These figures indicate exposure to volcanic hazards based on direct fatalities due to hazards from historic eruptions at these distances. An overwhelming majority of Guatemala's population lives at a distance from a volcano that could threaten their lives. Therefore, volcanic hazard assessment and disaster risk mitigation should not be considered as secondary but as crucial to protect a population living with a continual threat.

In Guatemala the effective integration of volcanic hazard assessment and risk mitigation is critical to a significant portion of its population. With whom does responsibility for this task lie? What efforts are being made to bridge the gap? Scientists must assume some responsibility: they "… fundamentally have a moral obligation to consider the potential social and ethical implications of their work in the formulation of advice based on science" (Douglas [2009] via

Donovan [2019]). However, scientists cannot be fully responsible - decisions to reduce risk are rarely theirs to make. Bridging this gap relies on effective communication between scientists and decision-makers [Barclay et al., 2008]. The manner of this communication is critical. The weaknesses of the traditional 'linear' direction of communication from scientists towards the public and decision-makers are summarized by Donovan and Oppenheimer [2014].

Many volcanically active countries show examples of difficulties in collaboration between different stakeholders with different priorities. The long-term eruptive crisis of Volcán Tungurahua in Ecuador, including early difficulties in communication [Tobin and Whiteford, 2002], provides a close-to-home parallel to Fuego in Latin America. However, many environments have shown that despite difficulties in collaboration, persistent effort has resulted in significant improvement. The development of Colombia's scientific, academic, and risk reduction institutions since the 1985 tragedy of Nevado del Ruíz is a good example [Pallister and Ewert, 2015]. In comparison, understanding the relationships between analogous Guatemalan institutions is a challenge. It is strikingly difficult to find concrete information on how Guatemala's national natural hazard monitoring and disaster risk reduction (DRR) institutions (INSIVUMEH and CONRED, respectively) communicate with each other, as well as how they correspond with the communities they serve. The questions posed above – With whom does the responsibility for integrating hazard assessment and risk mitigation lie? What efforts are being made to bridge the gap? – have not been satisfactorily asked in Guatemala, let alone answered. Guatemala follows the UNDRO-USGS scheme of risk management laid out in [Macías and Aguirre, 2006]. The assumptions in this model of risk management appear in Table 1.1.

Assumptions from UNDRO-USGS scheme
- People are aware of volcanic hazards and wish to protect their communities - Laws exist at the local, regional, and national levels that make it possible to carry out protective measures; - There is ample scientific knowledge to construct alternative scenarios for eruptions and their destructive effects; - It will be possible to disseminate warnings with sufficient lead time for people to take protective action; an emergency plan can be put in place.

Table 1.1: Assumptions from UNDRO-USGS scheme employed in many Latin American countries with active volcanoes. From Macías and Aguirre [2006].

The same UNDRO-USGS scheme includes several social actors. These actors can be recognized in Guatemala's current volcanic risk management environment and are included in parentheses below each actor:

1. A group of scientists in charge of monitoring the volcano who issue forecasts to appropriate authorities about the probability and nature of the risks of volcanic activity. They would not intervene in the activities of civil authorities in charge of protecting the population.
   (INSIVUMEH)

2. An emergency management committee that includes public officials and representatives from other community organizations, which interprets and uses the scientific knowledge for the population's protection.
   ("Mesa" including COCODE – for more detail see Chapter 3)

3. An effective mass communication system that disseminates the decisions of the emergency management system and provides people with information about the volcanic threat and the recommended protective actions.
   (INSIVUMEH bulletin reports and CONRED radio – for more detail see Chapter 3).

Macías and Aguirre [2006] noted several flaws in this scheme in case studies in Nicaragua, Mexico, and Ecuador. Given the challenges discussed above – prioritizing scientific monitoring when more basic needs are not being met, balancing the various priorities of different stakeholders, coping with unpredictability of the monitored physical system – and the difficulty of obtaining information on the responsibilities of Guatemala's scientific and DRR institutions, it is likely that if the Guatemalan system were included in the case studies by Macías and Aguirre [2006], it would present similar flaws. However, the paucity of information that I have mentioned means that this hypothesis cannot easily be (dis)proven. Simply put, at Volcán de Fuego we do not have enough information to make an argument. There is not enough information on local knowledge of volcanic hazards, on laws regarding protective measures against volcanic activity, or on stakeholder networks for communicating information on volcanic activity, in order to argue whether Guatemala's current volcanic risk management environment is satisfactory to protect lives and livelihoods against the current level of eruptive activity from Fuego (and ideally, against future increases in eruptive activity). A case study of a single volcano provides an excellent opportunity to provide such information.

1.1.2 The case for case study research

The case study is a common research design in volcanology. Its advantages include the opportunity to gather "detailed information of a single example of a class of phenomena" [Abercrombie et al., 1990]. Detractors of this design commonly question its pertinence beyond the study site [Flyvbjerg, 2006]. Actually, lessons from case studies in both physical and social volcanology have been successfully implemented elsewhere. For example, the multi-stakeholder participation pioneered in the Pacific island of Savo [Cronin et al., 2004] has been trialled in places as distinct as Papua New Guinea [Mercer and Kelman, 2010] and Costa Rica [van Manen et al., 2015].

It may seem that in 2021 there is no stone of the world left unturned. In fact, the global volcanic map is incomplete and, in some places, only faintly sketched. While volcanoes like Stromboli and Kilauea have for decades been the natural laboratory for the volcanologist, still many more demand more comprehensive study of their behaviour [Ogburn et al., 2015]. In Latin America, several volcanoes feature prominently in both physical volcanology and volcanic risk literatures, such as Tungurahua (e.g., Lane et al. [2003], Arellano et al. [2008], Stone et al. [2014], Armijos et al. [2017] and Volcán de Colima (e.g., Gonzalez et al. [2002], Gavilanes-Ruiz et al. [2009]), but many others remain under-studied despite high levels of eruptive activity and proximity to vulnerable populations. Guatemala is particularly under-represented in volcanic risk literature [Lechner and Rouleau, 2019]. I believe that the settlements that flourish on Fuego's flanks, as well as the volcano's continuing activity, urgently demand study. As to whether results of a case study could be generalized, Flyvbjerg [2006] perceptively states, "One can often generalize on the basis of a single case ... formal generalization is overvalued as a source of scientific development, whereas the "force of example" is underestimated". Flyvbjerg cites the Popperian example of a theory ("all swans are white") to highlight the validity of the case study as research design: the detailed nature of the case study is particularly suited to identifying black swans that may appear white to less exhaustive research designs. In this sense, the case study is an excellent way to test a general theory. (For instance, the statement, "all people are prepared to evacuate from an eruptive crisis of Fuego" is false if even one resident disagrees.) Even if results from a case study cannot be generalized, they still represent new knowledge at the volcano itself. Such knowledge is highly valuable to the society around a volcano in evaluating approaches to risk and vulnerability to natural hazards:

> "... more transparency and more information about the most vulnerable areas and groups are needed in order to make more appropriate information available to national and local decision makers for risk and vulnerability reduction, and also to provide the growing global disaster-response community with more precise knowledge on who to target first in or before a disaster situation."
>
> [Birkmann, 2007]

Whether results are relevant only at home or applicable abroad, the case study is likely to provide information valuable to both scientists and decision-makers for vulnerability and risk reduction.

There are numerous reasons for choosing Fuego as a case study subject beyond its under-representation in volcanology literature. First, it presents an unusual opportunity to study a currently active volcano. The thesis narrative begins in 2015 with observations from the Guatemalan national scientific institute (INSIVUMEH) of an increase in the frequency of Fuego's paroxysmal eruptions ("paroxysms", see Chapter 2). These eruptions continued during the research project, allowing me to study a developing eruptive regime while I developed as a researcher. Second, my choice of Fuego as a case study was motivated by the close correlation of that developing activity with eruptive hazards. Paroxysms are the primary formation mechanism for pyroclastic flows at Fuego. These flows are a major hazard for local populations, and the only response guaranteed to ensure safety is evacuation. The more frequent paroxysms since 2015 represent an increase in pyroclastic flow hazard. Improved understanding of recent paroxysmal activity may aid both INSIVUMEH (through establishing baselines and identifying potential paroxysmal triggering mechanisms) and the national institute for disaster risk reduction (DRR), CONRED (through identifying thresholds that can be translated to levels of tolerable risk). Beyond this, my choice of Fuego as a case study was strongly motivated by my desire to represent the experiences of people living beside the volcano. Remote sensing captures Fuego's activity with the advantage of being relatively risk-free. But Fuego is a major source of risk to local people who may experience the consequences of its activity. Both the Mayans and the Spanish knew the volcano as "the source of fire", remarkable for the frequency and the ferocity of its eruptions[1]. The question of why people live here, and what can help us better understand it, is vital to inform future strategies to protect against ongoing volcanic hazards. Excepting a single qualitative study [Graves, 2007], the experience of living with Fuego has not been told in locals' own words. To me, Fuego presented an excellent candidate for investigation into the motives, priorities, and experiences of people who are vulnerable to its activity.

How to satisfy multiple motives in a single case study is a matter of some difficulty. Previous theses have tackled motives separately in discrete chapters [Escobar Wolf, 2013], while others have taken a fully integrated interdisciplinary approach from the first page [Hicks, 2012]. My thesis chooses the discrete approach favoured by Escobar Wolf [2013], whose case study is also of Fuego. This approach suits the "state of play" at Fuego itself, reflected in the current lack of communication between associated scientists and decision-makers (see Chapters 3 and 4). By juxtaposing scientific observations and local experiences, this thesis outlines the current state of volcanic risk at Fuego and argues that artificial separation of the two creates "blind spots" in both scientific and non-scientific communities. Acknowledging these blind spots clears a path forwards for future interdisciplinary study that would address these flaws. I explain the methods employed in this approach in Section 1.2.4.

In summary, this thesis seeks to contribute knowledge of Volcán de Fuego in three areas: (1) recent eruptive activity, especially paroxysmal eruptions; (2) generation and development of hazards associated with paroxysms, particularly lava and pyroclastic flows; (3) experiences and priorities of people in nearby communities who are vulnerable to these hazards. Given that the only form of risk mitigation effective against pyroclastic flows is evacuation, this thesis will

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[1] "Fuego" means "fire" in Spanish, and Fuego's name in the indigenous Kaqchikel language is "Chi'gag", meaning "Where the fire is". [Tedlock, 1985]

explore (3) through reference to previous eruptive activity requiring evacuation. Previous theses have conducted both physical volcanology and volcanic risk perception research at Fuego to provide new insights into each [Escobar Wolf, 2013]. This work follows the same interdisciplinary principle. However, through its juxtaposition of scientific observations and lived experience, this thesis concludes that including one without the other in volcanic risk mitigation strategies omits knowledge that is crucial for the success of these strategies.

1.2 Methodological approach and thesis structure

This section presents the primary research aims of this thesis and outlines the methods used to achieve those aims. Before that, it is crucial to provide context by presenting the philosophical framework for this research and discussing some challenges particular to interdisciplinary research.

1.2.1 The doors of perception: defining a philosophical framework

Everyone has a door through which they view the world. The prudent researcher considers the framing of their door before making observations of the world beyond – but this consideration can be a bewildering process. The researcher's frame is defined by fundamental philosophical "worldviews", a worldview being "a basic set of beliefs that guide action" (Guba, 1990, pg. 17 via Creswell [2014]). Worldviews are alternatively defined as "epistemologies and ontologies" [Crotty, 1998]. Epistemology is concerned with the nature and validity of knowledge – "how do we know what we know?" [McGrath, 2020], while ontology concerns the nature of being, specifically "the nature of the world and what we can know about it" (Snape and Spencer [2003] via Al Saadi [2014]). Of the worldviews that define how a researcher interacts with the world beyond their door, two widely-recognized positions are positivism and interpretivism [Raddon, 2010]. These positions are often placed in direct opposition to each other [Ryan, 2018], although some have argued that the worldviews have more similarities than traditionally recognized [Weber, 2004].

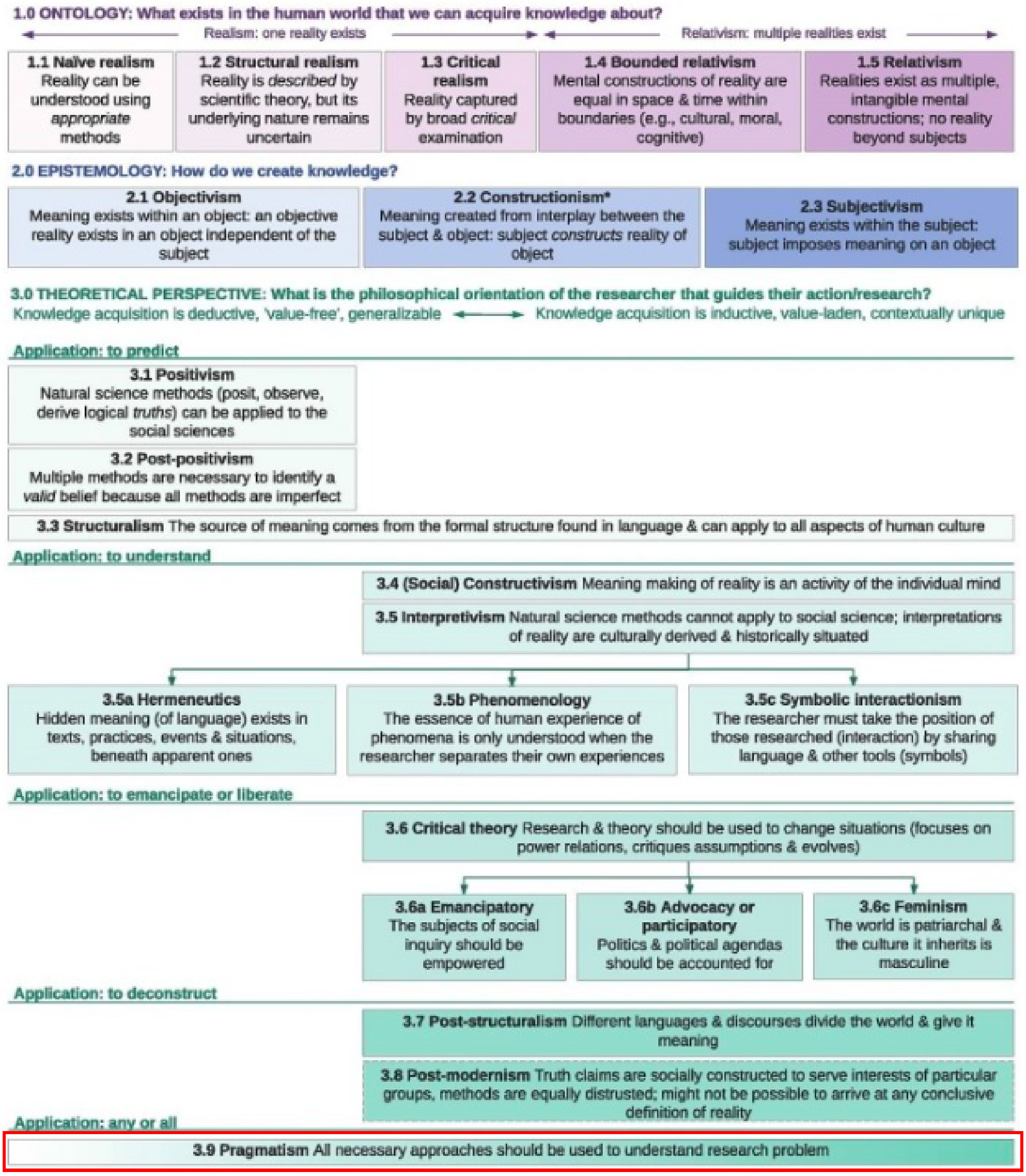
The interdisciplinary researcher faces a unique challenge in that they appear to approach their research with multiple, contrasting worldviews. The natural sciences researcher is the quintessential positivist: they consider themselves a disinterested observer of the world beyond their door (their ontological position), and their primary concern is uncovering the objective truth that is present in that world (their epistemological position) [Weber, 2004, Raddon, 2010](see Figure 1.3). By contrast, the interpretivist researcher considers themselves a 'detective' of knowledge, intrinsically involved in the world they observe (ontological position), a world in which they unearth subjective truths by interpreting the meaning of what they observe (epistemological position) [Raddon, 2010] (Figure 1.3). The interpretivist researcher is common in the social sciences. One can appreciate why positivist and interpretivist approaches have been set in opposition to each other: a positivist researcher might state, "The objective truth is out there –

and with the right methods, we can capture it.” The interpretivist researcher would reply, “The truth is out there – but it’s complex, and coloured by meanings, motivations, and values of social actors.” [Raddon, 2010]. How can these two researchers be reconciled within a single thesis? Adding to the confusion of defining one’s research position is the frequent confusion between philosophical and technical issues [Bryman, 2016].

Fortunately, there are several clues out of the philosophical labyrinth above. First, while research methods superficially reveal the philosophical position of the researcher (for instance, in-depth interviews favoured by many social researchers suggest they hold an interpretivist worldview [O’Donoghue, 2018]), there is growing support for research that combines multiple methods and philosophical positions: “a well-established literature now exists that addresses how case studies – historically, an interpretive research method – ought to be conducted within a positivist tradition” [Weber, 2004]. Second, the positivist/interpretivist philosophical dichotomy is simplistic. Multiple other research philosophies exist that better serve the purposes of the interdisciplinary investigator. Pragmatism is a good choice. Instead of the positivist, who seeks to explain or predict, or the interpretivist, who wishes to understand, the pragmatist can apply either of the above – or other approaches – to solve their problem [Moon and Blackman, 2014] (see Figure 1.3). The researcher with the pragmatic worldview is primarily concerned with solving the research problem with any methods available [Creswell, 2014]. This pluralist approach allows the researcher to use both quantitative and qualitative methods to solve the problem in front of them, and is increasingly encountered in issue-driven research as society and the environment continue to merge [Hicks, 2012]. For a researcher like me who is principally motivated by the issue at hand, “pragmatism opens the door to ... different worldviews, and different assumptions, as well as different forms of data collection and analysis” [Creswell, 2014].

1.2.2 Interdisciplinarity: the importance of combining physical and social science

Volcanoes and people have coexisted for millennia [Schmitt et al., 2014]. Given the fascination that volcanoes hold for human curiosity, one might imagine that the intersection between eruptive and human activity has a long and illustrious research history. This is not the case. This thesis joins a growing library of interdisciplinary volcanic risk theses (e.g., Donovan [2010], Lowe [2010], Hicks [2012], Delos Reyes [2019]). These comprise four prominent interdisciplinary volcanic risk theses completed in the last decade. Considering the hundreds of single-discipline volcanic theses published in the same timescale, an interdisciplinary approach to volcanology is still highly unusual. However unusual, this approach is deeply valuable, because focussing exclusively on scientific observations misses an opportunity to develop a holistic view of risk that acknowledges the parallel but different experiences of non-scientific stakeholders. The ~3.5 years of a typical PhD thesis provides ample time for an interdisciplinary approach. The benefits of undertaking an interdisciplinary UKRI-funded PhD studentship are presented in Donovan



1.0 ONTOLOGY: What exists in the human world that we can acquire knowledge about?

Realism: one reality exists

Relativism: multiple realities exist

1.1 Naïve realism Reality can be understood using *appropriate* methods

1.2 Structural realism Reality is *described* by scientific theory, but its underlying nature remains uncertain

1.3 Critical realism Reality captured by broad *critical* examination

1.4 Bounded relativism Mental constructions of reality are equal in space & time within boundaries (e.g., cultural, moral, cognitive)

1.5 Relativism Realities exist as multiple, intangible mental constructions; no reality beyond subjects

2.0 EPISTEMOLOGY: How do we create knowledge?

2.1 Objectivism Meaning exists within an object: an objective reality exists in an object independent of the subject

2.2 Constructionism* Meaning created from interplay between the subject & object: subject *constructs* reality of object

2.3 Subjectivism Meaning exists within the subject: subject imposes meaning on an object

3.0 THEORETICAL PERSPECTIVE: What is the philosophical orientation of the researcher that guides their action/research?

Knowledge acquisition is deductive, 'value-free', generalizable ⟷ Knowledge acquisition is inductive, value-laden, contextually unique

Application: to predict

3.1 Positivism Natural science methods (posit, observe, derive logical *truths*) can be applied to the social sciences

3.2 Post-positivism Multiple methods are necessary to identify a *valid* belief because all methods are imperfect

3.3 Structuralism The source of meaning comes from the formal structure found in language & can apply to all aspects of human culture

Application: to understand

3.4 (Social) Constructivism Meaning making of reality is an activity of the individual mind

3.5 Interpretivism Natural science methods cannot apply to social science; interpretations of reality are culturally derived & historically situated

3.5a Hermeneutics Hidden meaning (of language) exists in texts, practices, events & situations, beneath apparent ones

3.5b Phenomenology The essence of human experience of phenomena is only understood when the researcher separates their own experiences

3.5c Symbolic interactionism The researcher must take the position of those researched (interaction) by sharing language & other tools (symbols)

Application: to emancipate or liberate

3.6 Critical theory Research & theory should be used to change situations (focuses on power relations, critiques assumptions & evolves)

3.6a Emancipatory The subjects of social inquiry should be empowered

3.6b Advocacy or participatory Politics & political agendas should be accounted for

3.6c Feminism The world is patriarchal & the culture it inherits is masculine

Application: to deconstruct

3.7 Post-structuralism Different languages & discourses divide the world & give it meaning

3.8 Post-modernism Truth claims are socially constructed to serve interests of particular groups, methods are equally distrusted; might not be possible to arrive at any conclusive definition of reality

Application: any or all

3.9 Pragmatism All necessary approaches should be used to understand research problem

FIGURE 1.3. Overview of ontological, epistemological, and philosophical perspectives present in social science research. Elements are more multidimensional when read from left to right. My ultimate approach (pragmatism) is highlighted in red. Adapted from Moon and Blackman [2014].

et al. [2011]. Interestingly, the development of Katherine Donovan with her thesis (see Donovan [2010]) anticipates my own development, placed at the intersection between physical and social volcanology, and involving a transition towards the latter as the project progressed.

Although the theses cited above illustrate growing support for combined approaches to volcanic risk, much more remains to be achieved. Research in physical volcanology still suffers from a lack of connection to the social. Scientists continue to publish exquisitely detailed studies of eruptive behaviour without considering how conclusions of said study may travel beyond the scientific sphere [Donovan, 2019]. Consider in articles on volcanic eruptive activity how frequently the following sentence (or some variation thereof) appears: “[our results] could assist volcanic mitigation efforts” [Aldeghi et al., 2019]. These statements are true but are of limited assistance to such efforts if other factors are ignored. Whether seen from the scientist’s desktop, the decision-maker’s desk, or the local’s kitchen table, an explosion at Fuego’s summit has significance. Sometimes, the scientist’s perspective is considered to be the most accurate. However, this opinion is dangerous, as it both discredits the validity of other perspectives and ignores the relative biases implicit in the scientific perspective:

> When we look at the objects of scientific knowledge, we don’t tend to see the experiences that underpin them. We do not see how experience makes their presence to us possible. Because we lose sight of the necessity of experience, we erect a false idol of science as something that bestows absolute knowledge of reality, independent of how it shows up and how we interact with it.
>
> [Frank et al., 2019]

I do not wish to discredit the validity of the scientist’s perspective, nor does this thesis aim to place scientific and local perspectives in opposition to each other as different truths. Rather, by juxtaposing perspectives derived from the scientist’s desktop and the local’s table, I wish to present multiple experiences from different people that complement each other as part of a larger whole. A holistic approach to volcanic risk should include a variety of voices. Writing a thesis that combines approaches to address multiple perspectives is a large challenge that has produced this particularly stout thesis. However, I consider my time well-spent in this endeavour. I believe that by engaging with both physical and social scientific perspectives I have developed into a well-rounded researcher. More importantly, I hope that my effort has produced work valuable to the people and institutions I have had the fortune to work with, from whose desks and tables I have studied Fuego for the last four years (Figure 1.4). These people include the observers and volcanologists of INSIVUMEH, the technicians and risk managers of CONRED, and the people in communities around Fuego’s flanks, many of whom are my friends. I hope this thesis in some way defends their continuing safety in the event of a future eruption of Fuego.

FIGURE 1.4. One of my goals in writing this thesis was to contribute to the future security of people living in rural communities around Fuego. This image was taken during my fieldwork in 2019 conducting qualitative research for Chapter 3.

1.2.3 Thesis goals

The primary aim of this thesis is to examine recent paroxysmal eruptive activity at Fuego volcano through scientific observations and lived experience and to promote their integration within risk reduction strategies. This can be divided into nine broad goals:

- To characterize the recent (1999 – 2018) eruptive activity of Fuego through satellite remote sensing and other datasets;
- To discuss models that explain the sudden change in eruptive activity beginning in 2015;
- To investigate experiences of residents of communities near Fuego of (1) previous eruptive activity and volcanic hazards, and (2) their responses to the same;
- To compare results from remote sensing data with peoples' experiences to understand how different perspectives influence volcanic risk at Fuego;

- To evaluate how experience of and response to eruptive activity influence the success of current volcanic risk mitigation policy;
- To determine, through analysis of geophysical data, timescales associated with paroxysmal eruption in the new (since 2015) eruptive regime;
- To explore timescales associated with response to recent eruptions;
- To explore, by comparing the timescales above, the likelihood of current volcanic risk mitigation policy at Fuego providing sufficient warning to protect lives of local residents;
- Finally, from answers to the goals above, to consider (1) implications for the continued risk to lives of local residents from eruptive hazards associated with explosive paroxysms of Volcán de Fuego, and (2) opportunities to mitigate this risk.

The position of each of these goals in a volcanic risk framework is indicated in Figure 1.2.

1.2.4 Research methods employed

Previous studies on Fuego tend to employ satellite remote sensing methods or short-term deployment of geophysical equipment. Satellite observations have revealed long-term trends in activity [Lyons et al., 2010]. Meanwhile, multiparametric ground-based remote sensing has provided insight into upper conduit dynamics [Nadeau et al., 2011]. Comprehensive surveys and qualitative interviews eloquently capture local experiences [Graves, 2007, Escobar Wolf, 2013]. This thesis combines the above methods in a single interdisciplinary work whose novel contributions to existing literature include combining satellite with qualitative visual observations, and in its choice of geophysical signals (RSAM, SO_2, and thermal) used to communicate behavioural changes of Fuego over multiple timescales. In addition, although major population growth in recent years has greatly amplified the voices around Fuego, there have been no studies of local experiences of eruptive activity since 2007. The change in Fuego's paroxysmal eruptive regime in 2015 represents a new challenge for both scientists (i.e., INSIVUMEH) and DRR staff (i.e., CONRED). This work is the first to simultaneously consider physical and social perspectives of Fuego's paroxysmal eruptive behaviour since a major change in this has significantly increased volcanic risk to a burgeoning local population.

1.2.5 Positionality

In Section 1.2.1, I considered different philosophical frameworks for approaching the research world. I mentioned the particular challenge for interdisciplinary researchers in defining their framework before offering pragmatism as a solution for the flexibility it affords such researchers in how they interact with their multifaceted world. In Section 1.2.2, I noted several examples of prominent interdisciplinary theses in volcanology. I also gave my personal motivations for choosing an interdisciplinary approach. This section briefly outlines my positionality towards my research, which I explicitly define relative to specific chapters in this text (for thesis structure, see Section 1.3). Because each contains elements of the other, a researcher's philosophical orientation, disciplinarity, and positionality can become tangled. To clarify, then, Sections 1.2.1 and 1.2.2 defined, respectively, possible philosophical frameworks for defining my research, and the disciplines in which I conduct this research. In this section I explicitly position myself in relation to my research in each of the three data chapters that follow.

The structure and content of Chapter 2 appears to correlate with the "positivist" philosophical approach typically assumed within natural sciences research. This approach aims to predict and to observe, and assumes that acquisition of knowledge is value-free. The researcher is idealized as a disinterested individual who can derive logical truths from the natural world that they observe (see Figure 1.3). This approach is so common within the natural sciences as to be almost universally assumed rather than explicitly stated. However, during the course of this thesis it became clear to me that I could not be this "disinterested individual". While doing fieldwork for Chapter 3, I realized that I was hopelessly entangled in the world that I was observing. By living in Guatemala, by interacting with elements of local culture or talking to people or asking questions about Fuego's history, I was simultaneously being influenced by, and exerting an influence on, my immediate environment. I then understood that I would have to define where I stood in relation to my research. This was most explicit in my research on human experience of eruptive activity at Fuego, given that this research has explicit cultural, historical, social, and political elements, and positionality is: "the stance or positioning of the researcher in relation to the social and political context of the study" [Coghlan and Brydon-Miller, 2014]. To expand:

> Within interpretative research there is an appreciation that the research participant, the research field and the researcher are involved in an dynamic process whereby each effects the others...researchers appreciate that there are a variety of factors in their own intellectual and social development which can affect the manner in which they relate to the social world, and interpret both their own responses and those of research participants.
>
> [Oliver, 2013]

However, on further consideration it becomes apparent that I should define my positionality with regards to *all* of the research presented in this thesis. While the data presented in Chapter 2 and some of Chapter 4 derive from instrumental sources, I gathered and analysed these data in an environment with social and political elements. For example, the RSAM data I analyze in these chapters were obtained through negotiations with colleagues in INSIVUMEH. These colleagues faced political debate in sharing their data with a collaborator outside their institution.

Therefore, in *both* the physical and social aspects of my thesis, I entered my world of study carrying effects that coloured my ensuing interactions with it. My gender, nationality, culture, and training all affect my approach both to tracing recent eruptive activity of Volcán de Fuego and to capturing local residents' experiences of eruptions and evacuation. I am a middle-class, White British woman. I approached my subject as a student seeking primarily to build her own knowledge of both the human and natural environment at Fuego. When conducting interviews, I encountered a similar scenario to that presented in Kusek and Smiley [2014]: beginning my research concerned that I might not conduct a successful interview, particularly with male interviewees. Instead, I found that I quickly gained interviewees' confidence and was able to discuss sensitive topics easily, perhaps because I was perceived as a more empathetic listener (open to receiving stories of emotional intensity) than if I had been a man [Kusek and Smiley, 2014]. I would like to stress that I do not hold with this convention of gender roles myself – only that it is a plausible source of peoples' openness with me in a socially conservative country like Guatemala. That conservatism worked against me too. I faced the difficulties of being a lone female researcher in a "macho" Latino culture. This was most evident to me when taking additional precautions to ensure my safety in the field. I did not experience direct threats or harassment while in Guatemala, but I was aware it was an everyday part of many women's lives there. This caution perhaps afforded me less freedom of movement than a man in my position. An interesting theory is that this stance – the "trade-off" between collecting good data and ensuring one's safety as a female researcher – is grounded in a disciplinary culture that positions itself with regards to an "idealized male positionality immune from gendered safety risks" [Ross, 2015]. Overall, I believe that my gender helped with the success of my research goals, as several other female researchers in Latin America have found [Cupples, 2002, Sundberg, 2003].

Being from a country other than Guatemala proved to be an asset and a setback. On one hand, I encountered cultural factors I was unfamiliar with. I found it difficult to understand some of the institutional politics that complicated data sharing and collaboration between me and the volcanologists of INSIVUMEH. Like other 'outsider' researchers, I sometimes struggled to accurately represent my interviewees' perspectives, and translation of experiences from Spanish to English required careful negotiation [Merriam et al., 2001]. However, my interviewees (correctly) interpreted my curiosity in their experience as an outsider's desire to understand an unfamiliar scenario, and responded generously. My outsider status and subsequent interest in people's lives, so different from my own, allowed me to build trust quickly. I could also benefit from locals' surprise and pleasure at my ability to speak fluent Spanish. I believe this contrasted with their expectations of me as a foreigner adopting the 'external-outsider' research position of working in a community different from the one I was socialized in [Mercer et al., 2010].

I would like to conclude by explaining the purpose of this thesis, and how the different chapters build on each other to create a single coherent argument. The purpose of this thesis is to contribute new knowledge on eruptive activity and human experience at Volcán de Fuego. This knowledge may provide insight into local volcanic risk and its mitigation. "Risk" actually has multiple definitions, as shown in Table 1 of Brooks [2003]. An early definition by Crichton [1999] is:

> “Risk” is the probability of a loss, and depends on three elements, hazard, vulnerability and exposure.
>
> [Crichton, 1999]

Crichton conceptualized the three elements of hazard, vulnerability, and exposure as sides of a "risk triangle". If any element or side of the triangle increased, risk would also increase [Crichton, 1999]. Alternative frameworks for understanding disaster risk have been proposed, but Crichton’s work on the relationship between hazard, vulnerability, exposure, and risk is still widely used, as shown in Figure 1.5.

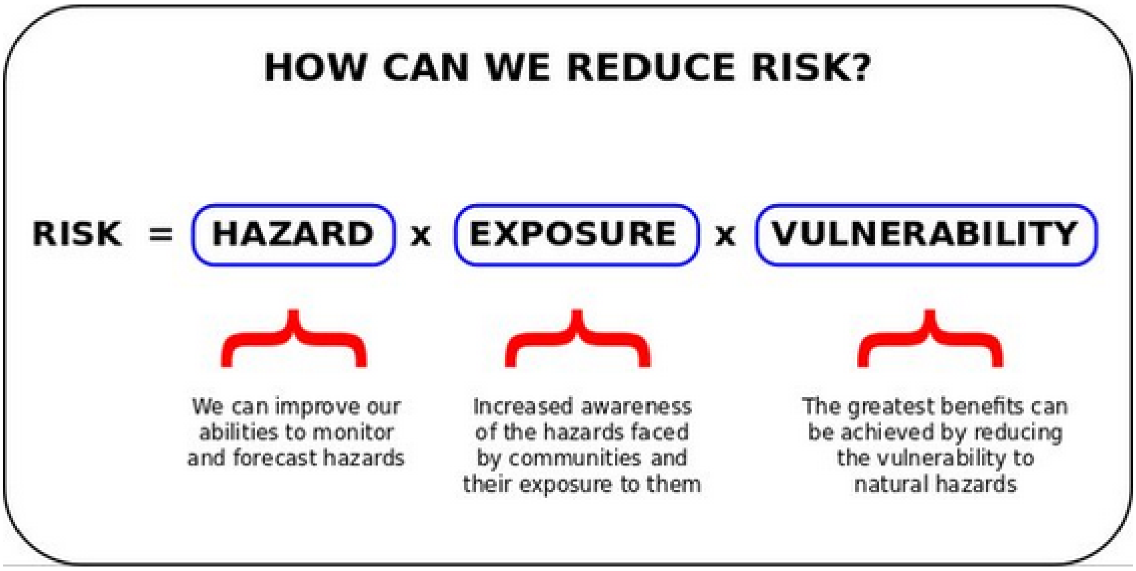


FIGURE 1.5. The equation for disaster risk, showing how hazard, exposure and vulnerability are involved in the calculation. From Tostevin [2014].

I have provided this exposition to explain the contribution this thesis makes to understanding volcanic risk at Fuego. This project began in September 2016, approximately 18 months after INSIVUMEH had started reporting on more frequent lava effusion and explosive summit activity at the volcano. When I began this project, it was clear that despite the change reported by INSIVUMEH, there was a relative shortfall of recent (<5 years) knowledge available on (1) any potentially dangerous volcanic processes of Fuego, including lava flows, pyroclastic flows, lahars, and ashfall (i.e., its hazards); (2) the conditions determined by physical, social, economic and environmental factors or processes that increase susceptibility of individuals, communities, and systems around Fuego to the impacts of (1) (i.e., vulnerability to volcanic hazards [2]. How can we have a useful discussion of volcanic risk if we do not understand that factors that contribute to this risk?

Each chapter contributes to this thesis's central goal of contributing to knowledge of volcanic hazards and vulnerability to inform understanding of volcanic risk at Volcán de Fuego. This introduction lays out my rationale for choosing this goal, discusses the challenge of attempting this from an interdisciplinary perspective, and presents the tools I use to accomplish the goal. Chapter 2 provides the reader with a foundation for understanding eruptive activity and volcanic hazard at Fuego through a comprehensive review of previous literature. In addition, Chapter 2 contributes new knowledge on Fuego's hazards through results presented through analysis of satellite imagery and bulletin reports. I present MIROVA as a tool to assist INSIVUMEH in their ability to monitor and forecast volcanic hazards at Fuego, which is an important component of reducing volcanic risk as shown in Figure 1.5. Chapter 2 briefly considers how different populations around Fuego may be vulnerable to different hazards (see Section 2.6) before exploring how Fuego's activity has changed since 2018 (see Section 2.6.4).

Chapter 3 may appear an abrupt change from Chapter 2. In fact, the two chapters are purposefully juxtaposed in order to illustrate the different variables that must be considered together to present a holistic portrait of risk at a volcano. These elements are shown in Figure 1.5. In this equation, as in Crichton's risk triangle, reducing any one variable will also reduce volcanic risk. While Chapter 2 informs understanding of volcanic hazards at Fuego, it resolves only part of a greater uncertainty. Chapter 3 resolves another part. By exploring stakeholders' experiences of previous eruptive activity and their responses to such, Chapter 3 gives insight into the dynamics of current risk mitigation policy at Fuego, i.e. evacuation. This chapter does not provide direct analysis of vulnerability to volcanic hazards, which would involve investigation of social, economic, and political forces occurring on timescales much greater than the activity presented in 2. Instead, Chapter 3 studies priorities and collective memory of various stakeholders during eruption and evacuation. Study implications then inform where work may be done to increase awareness of hazards (i.e., reduce exposure) or to address the conditions that make people vulnerable to hazard (i.e., reduce vulnerability).

Chapter 4 intertwines the threads of hazard and experience explored in Chapters 2 and 3 through analysis of paired timelines of eruption and response at Fuego. Analysis of multiparametric datasets builds on work in Chapter 2 by tracing patterns in geophysical signals and characterizing timescales over which an eruption of Fuego waxes, climaxes, and wanes. Interview

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[2] these definitions are consistent with those used in Chapters 3 and 4

data, CONRED infographics, and INSIVUMEH bulletin reports provide material to characterize timescales over which a response to eruption occurs. These timescales are then paired to discuss redundancies and shortfalls in the current risk mitigation policy of self-evacuation first presented in Chapter 3. The central question to answer is: what warning time for imminent eruptive activity is necessary to mitigate risk to local residents? Is this time achievable with the current monitoring and risk reduction systems? By pairing timescales of physical hazards and social responses, and by pairing geophysical and interview datasets, this chapter is a truly interdisciplinary work consistent with the goals stated in 1.2.3.

Chapter 5 gathers the results of previous chapters to summarize how this thesis has brought forward our understanding of volcanic risk, and the elements that make it, at Volcán de Fuego. The final chapter also provides a road map beyond the local view of Fuego, by reflecting on how lessons from this thesis may be applied abroad, and vice versa. Chapter 5 also proposes future enrichment of discussions of volcanic risk by incorporating concepts and methodologies used in the broader discipline of natural hazards research.

1.3 Thesis structure

This thesis comprises five chapters, including introduction and conclusions. Chapter 2 considers evidence derived from remote sensing data for an accelerating cycle of paroxysmal eruptions at Fuego between 2015 and 2018, and discusses implications of the hazards associated with this eruptive cycle. The chapter frames this eruptive cycle within Fuego's longer eruptive history. Various models are debated to explain the change in eruptive cycle. Results end in June 2018. However, an update in March 2021 provides the sequel of what will follow in Fuego's eruptive narrative.

In Chapter 3 I chronicle stakeholders' experiences of eruption and evacuation that I gathered from qualitative research I conducted in 2018 and 2019. In this chapter, I directly compare local experiences with both scientists' testimonies and with timeseries data from Chapter 2. Results have serious implications of experiential differences for risk mitigation efforts before a future eruptive crisis. Locals' experiences diverge so greatly from scientists' experiences that even the concept of an eruption differs between the two groups. An interesting disparity between community members on the west and east flanks of Fuego emerges in terms of both their lived experience and their communication with INSIVUMEH/CONRED. This disparity has implications for risk mitigation that is consistent with studies at other volcanoes. Even though Chapter 2 concluded that paroxysms at Fuego have consistent precursors that may aid forecasting of future events, Chapter 3 illustrates that both scarcity of resources and direct experience of previous eruptions play a central role in influencing peoples' decisions in the face of eruptive crisis. If these factors are not considered in parallel with improved improved understanding of Fuego's physical system, efforts to reduce volcanic risk to local residents are likely to be of limited success.

Chapter 4 links SO_2, seismic, and thermal timeseries data to study the evolution of four eruptions within the new eruptive cycle. Analysis of timeseries data provide slight evidence of geophysical patterns consistently preceding paroxysm. Instead, these datasets give a timeline over which activity of Fuego evolves. Parallel timeline for response to eruption (i.e. evacuation) are calculated from interview data and CONRED infographics. In addition, a spatial component is introduced through volcanic hazard maps and evacuation routes. Timelines of eruption and response are compared, and embellished by spatial information, to plot the evolution of a hypothetical eruption and associated response time at Fuego. Results indicate that outside of RSAM, geophysical datasets do not often provide consistent precursors to paroxysm that can be used in forecasting. Timescales of eruption and response appear to be comparable at Fuego, and the implications of this for success of future evacuations are discussed. Additional discoveries include that pyroclastic flow generation is strongly linked to lava effusion in the same barranca, and that even when the decision to evacuate is taken, lahar hazard may hinder evacuation success. These discoveries are reviewed in the context of forecasting future paroxysms and evacuating to mitigate volcanic risk. Chapter 4 studies these factors through a mental models approach, and concludes by asking whether recognizing differences in mental models between stakeholders could be key in resolving future volcanic risk to local residents. This question forms a core element of my exploration of the interface between eruptive activity and human experience at Fuego.

In Chapter 5 I broaden my vision from a narrower focus on Volcán de Fuego to the larger picture of global volcanic risk. I study findings from volcanic environments worldwide to consider cautionary examples and to highlight scenarios where development is encouraging. These scenarios enlighten potential strategies for improving volcanic risk mitigation at Fuego. I include a series of recommendations for future volcanic risk mitigation practitioners.

For further reading, additional information is found in Appendices. These include: (1) the original project description (Chapter 6); (2) a table of all VEI ≥ 2 eruptive events at Fuego in historic (16^{th} - 20^{th} century) and recent (1999 – present) periods (Chapter 7); (3) a comprehensive database of all MIROVA values >200MW in the new eruptive regime (Jan 2015 – Jun 2018) associated with lead to, or evolution of, a paroxysmal eruption (Chapter 8); (4) questionnaires for Chapter 3 (English and Spanish) (Chapter 9); (5) various analytical results for Chapter 3 (Chapter 10); (6) a Python script used to detect cloud-free coverage for NicAIR results in Chapter 4 (Chapter 11); (7) a Python script for processing NicAIR images into SO_2 images for results in Chapter 4 (Chapter 12); (8) a PDF of NicAIR camera specifics, response functions, and calibration parameters (Chapter 13); (9) detailed description of the instrumentation of the NicAIR multispectral camera and data collected with the same (Chapter 14); (10) a literature review of remote spectroscopic remote sensing techniques (Chapter 15); and (11) a list of additional academic publications to which I have contributed (Chapter 16).

1.4 Summary

This introductory chapter presents the challenge of mitigating loss associated with natural hazards. Anthropogenic climate change has accelerated the frequency and impacts of hazards, while population growth has increased the number of people vulnerable. Although there is substantial knowledge of natural systems and their effects, associated human losses continue to grow. Solving this paradox, therefore decelerating increasing loss, requires more sophisticated answers than exclusively improving hazard knowledge and prediction.

There is a promising movement towards a fully interdisciplinary approach to volcanic risk. Both within academia and among DRR practitioners, it is increasingly recognized that the challenge of comprehensive volcanic risk mitigation is not to communicate the results of monitoring to an unsuspecting or uncaring public, but in engaging with local residents' knowledge and priorities resulting from different circumstances and access to resources. However, improved knowledge of volcanic hazards continues to be important. This thesis seeks both to improve knowledge of eruptive hazards and to promote integration of local knowledge within volcanic risk mitigation strategies through a detailed case study of Volcán de Fuego, Guatemala.

CHAPTER 2

AN ACCELERATING CYCLE

This chapter has previously been published as: ***Eruption frequency patterns through time for the current (1999 – 2018) activity cycle at Volcán de Fuego derived from remote sensing data: Evidence for an accelerating cycle of explosive paroxysms and potential implications of eruptive activity*** *in JVGR (see Naismith et al. [2019a]). The published manuscript was co-authored with Professor. Matthew Watson, Dr. Rüdiger Escobar-Wolf, Gustavo Chigna, Dr. Helen Thomas, Dr. Diego Coppola, and Carla Chun Quinillo. The project was conceived by IMW and AKN. REW provided data and contributed significantly both to the discussion and general direction of the manuscript. HET contributed significantly to the Discussion. DC provided MIROVA data and contributed to analysis. GC and CCQ provided RSAM data and INSIVUMEH bulletins and contributed to discussion of timelines. All authors made a substantial and intellectual contribution to the work and approved it for publication.*

2.1 Abstract

Volcán de Fuego is a stratovolcano in Guatemala that has produced over 50 VEI ≥ 2 eruptions since 1524. After two decades of quiescence, in 1999 Fuego entered a new period of eruptive activity that continues until the present day, characterised by persistent Strombolian activity interspersed with more occasional explosive eruptions. These eruptions are known as "paroxysms" and are characterized by sustained eruptive columns, rapidly-emplaced lava flows, and block-and-ash pyroclastic flows [Lyons et al., 2010]. The land surrounding Fuego accommodates tens of thousands of people, so greater understanding of its eruptive behaviour has important implications for hazard assessment. Nevertheless, there is relatively little literature that studies recent (since 1999) activity of Fuego in detail.

Using time-series analysis of remote sensing thermal data during the period 2000 – 2018 combined with recent bulletin reports, we present evidence for a new eruptive regime beginning in 2015. We find that this regime is defined by a greater frequency of paroxysmal eruptions than in previous years and is characterized by the following sequence of events: (i) effusion of lava flows and increase in summit explosive activity, followed by (ii) an intense eruptive phase lasting 24 – 48 hours, producing a sustained eruptive column, continuous explosions, and occasional pyroclastic flows, followed by (iii) decrease in explosive activity. We discuss various models that explain this increase in paroxysmal frequency, and consider its implications for hazard assessment at Fuego. We advocate the pairing of remote sensing data with monitoring reports for understanding long-term changes in behaviour of poorly-instrumented volcanoes. The results that we present here provide a standard for informed assessment of future episodes of unrest and paroxysmal eruptions of Fuego.

2.2 Introduction

Volcán de Fuego (3763 m asl; 14.47°N, 90.88°W), a prominent stratovolcano in southern Guatemala, produced a large eruption on 3rd June 2018 that generated pyroclastic flows and caused extensive damage and death in nearby communities. Despite being highly active, there is scant recent literature on the volcano. To provide context for this and other recent eruptions, we present an overview of the eruptive history of Fuego gathered from available academic literature. We also present new evidence, derived from long-term seismic and thermal databases, that points to the onset of a new cyclical eruptive regime.

"Volcán de Fuego" translates from Spanish as "Volcano of Fire". One of the first documented eruptions of Fuego exists in the letters of the conquistador Pedro de Alvarado, who recorded its activity in 1524 [Kurtz, 1913]. Fuego was also known for its ferocity to the Maya people, who christened it "Chiq'aq'", meaning "Fireplace" in the indigenous Quiché language [Tedlock, 1985]. With over 50 Volcanic Explosivity Index (VEI) ≥ 2 eruptions recorded since 1524, Fuego is one of the most active volcanoes in Central America (Global Volcanism Program, 2013), with a history of producing both violent Strombolian [Berlo et al., 2012, Waite et al., 2013] and sub-Plinian eruptions [Rose et al., 2008, Escobar Wolf, 2013]. During periods of activity, Fuego's behaviour consists of a persistent background of low-intensity Strombolian eruptions and ash-rich explosions [Patrick et al., 2007], which are interspersed with discrete events of larger energy and violence, referred to in this chapter as "paroxysms" (see Section 2.3 for full definition) [Martin and Rose, 1981, INSIVUMEH, 2012b]. Fuego's periods of activity occur between periods of repose lasting up to several decades [Martin and Rose, 1981]. A series of sub-Plinian eruptions in 1974 produced 0.2 km^3 of basaltic tephra that spread 200 km W [Rose et al., 2008]. This eruptive episode remains the largest since 1932. Since 1999, Fuego has been in a new period of eruptive activity [Lyons et al., 2010]. This period, like those before it, is dominated by persistent Strombolian activity producing lava fountaining and explosions and punctuated by occasional paroxysmal eruptions of greater energy and violence producing lava flows and (less frequently) pyroclastic flows [Escobar Wolf, 2013, Rader et al., 2015].

This chapter uses volcano radiative power (VRP) values from the Middle InfraRed Observation of Volcanic Activity (MIROVA) database [Coppola et al., 2012] to study recent eruptive activity at Volcán de Fuego. The method used is based on the approach by Coppola et al. [2012], analysing thermal output associated with volcanic activity at Stromboli between 2000 and 2011. In addition, analysis is focussed on correlating trends observed in the MIROVA Fuego data with records of eruptive activity from the Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología - *(National Institute of Seismology, Volcanology, Meteorology and Hydrology)* (INSIVUMEH), Guatemala's national scientific monitoring agency, and other datasets including Real-Time Seismic Amplitude Measurement (RSAM) values (INSIVUMEH, 2018) and Washington Volcanic Ash Advisory (VAA) reports (NOAA, 2018).

Paroxysmal eruptions at Fuego have been documented in previous literature, which has discussed various models that may trigger these events (e.g., Lyons et al. [2010]). However, the majority of such literature appeared prior to the eruptive activity discussed in this chapter. Therefore, the chapter reviews existing models for triggering paroxysm at Fuego and considers factors that may cause the observed increase in paroxysmal frequency since 2015. The chapter also examines the impacts of Fuego's eruptive hazards on exposed populations and infrastructures through study of specific paroxysmal eruptions occurring since 2015, including the eruption of 3rd June 2018.

2.3 Eruptive history of Volcán de Fuego

Forecasting the effects of future eruptions is inevitably informed by an understanding of past eruptions. This understanding includes a brief introduction to Fuego's tectonic setting, which has implications for the characteristics of volcanism observed. The majority of academic literature on Fuego's eruptive behaviour can be classified into one of three categories: prehistoric (before records began in 1524), historic (16th - 20th century), or recent (1999 – present). A full summary of notable eruptive events at Fuego during the historic and recent categories can be found in Appendix B (Chapter 7) of this thesis.

Fuego is located close to the triple junction of the North American, Cocos, and Caribbean tectonic plates (Figure 2.1 inset). The complex interplay of compressive and translational forces between these plates controls the behaviour of the Central American volcanic arc [Alvarez-Gómez et al., 2008, Authemayou et al., 2011], which is divided into seven segments of volcanic lineaments, of which Fuego occupies the furthest north [Stoiber and Carr, 1973, Burkart and Self, 1985]. Fuego is part of the Fuego-Acatenango massif, a volcanic complex consisting of five known eruptive centres younging towards the south (Figure 2.1) [Vallance et al., 2001]. The earliest evidence of volcanic activity at this complex is a lava flow dated to 234,000 ± 31,000 years; however, most of the complex was constructed after the Los Chocoyos ash eruption from nearby Lake Atitlan, 84,000 years ago [VanKirk and Bassett-VanKirk, 1996, Vallance et al., 2001]. At least two edifice collapse events have occurred since. The most recent, the collapse of La Meseta's eastern flank between 30,000 and 8,500 years ago, delivered over 9 km^3 of material to slopes to the south [Vallance et al., 1995], extinguishing activity at La Meseta and allowing for the subsequent development of volcanic activity that would eventually build Fuego [Martin and Rose, 1981, Vallance et al., 2001].

Fuego is the currently most active volcanic centre of the Fuego-Acatenango massif and has an upper age limit of 30,000 years [Vallance et al., 2001]. A minimum age of 8,500 years for Fuego has been calculated by extrapolating from a calculated effusion time for a sequence of lavas on Meseta's flank [Chesner and Rose, 1984]. An alternative minimum age of 13,000 years has been calculated by extrapolating from an estimated average eruption rate of 1.7×10^9 m^3 across the last 450 years [Martin and Rose, 1981].

Extremely little stratigraphic data exist for prehistoric eruptive activity at Fuego. This is in part because Fuego does not typically produce deposits that are sufficiently unique to be easily dated and thus constrain stratigraphic evolution. Some evidence for previous eruptions producing pyroclastic flows exists in the form of flow deposits that have been estimated by radiocarbon dating at 5370 ± 50, 3560 ± 70, 2170 ± 30, 1375 ± 45, 1050 ± 70, and 980 ± 50 years old [Vallance et al., 2001, Escobar Wolf, 2013]. Analysis of lava samples obtained from exposures in two of Fuego's seven barrancas, Barrancas Honda and Trinidad, reveals that prehistoric activity at Fuego has produced basalts, basaltic andesites, and andesitic lavas, with an evolution with time towards more mafic eruptive products. Prehistoric eruptive products were derived from fractional crystallization of plagioclase, olivine, augite, and magnesite from a basaltic melt rich in Al_2O_3 [Chesner and Rose, 1984].

The volume of information on Volcán de Fuego's eruptive activity improved greatly with the beginning of modern record-keeping that arrived with the Spanish in 1524. Records of a volcano's historic eruptive activity are rarely fully comprehensive, and those of Fuego are no exception. However, the greater the magnitude the eruption, the more certain the information [Escobar Wolf, 2013]. A summary of Fuego's eruptive activity between 1524 and 1999 illustrates that Fuego's occasional sub-Plinian and persistent Strombolian behaviours are interspersed with extended periods of repose lasting for years or even decades (Figure 2.2). The majority of eruptions of Fuego are contained within short intervals between repose: four periods of 20 – 70 years account for 75% of activity since 1524 [Hutchison et al., 2016]; these include at least five VEI 4 eruptions that have occurred between 1524 and the present day: in the years 1581-2, 1717, 1880, 1932 and 1974 [Escobar Wolf, 2013, Hutchison et al., 2016, Crosweller et al., 2020]. Because physical volcanology is a young science, there is no single measure existing for all these eruptions by

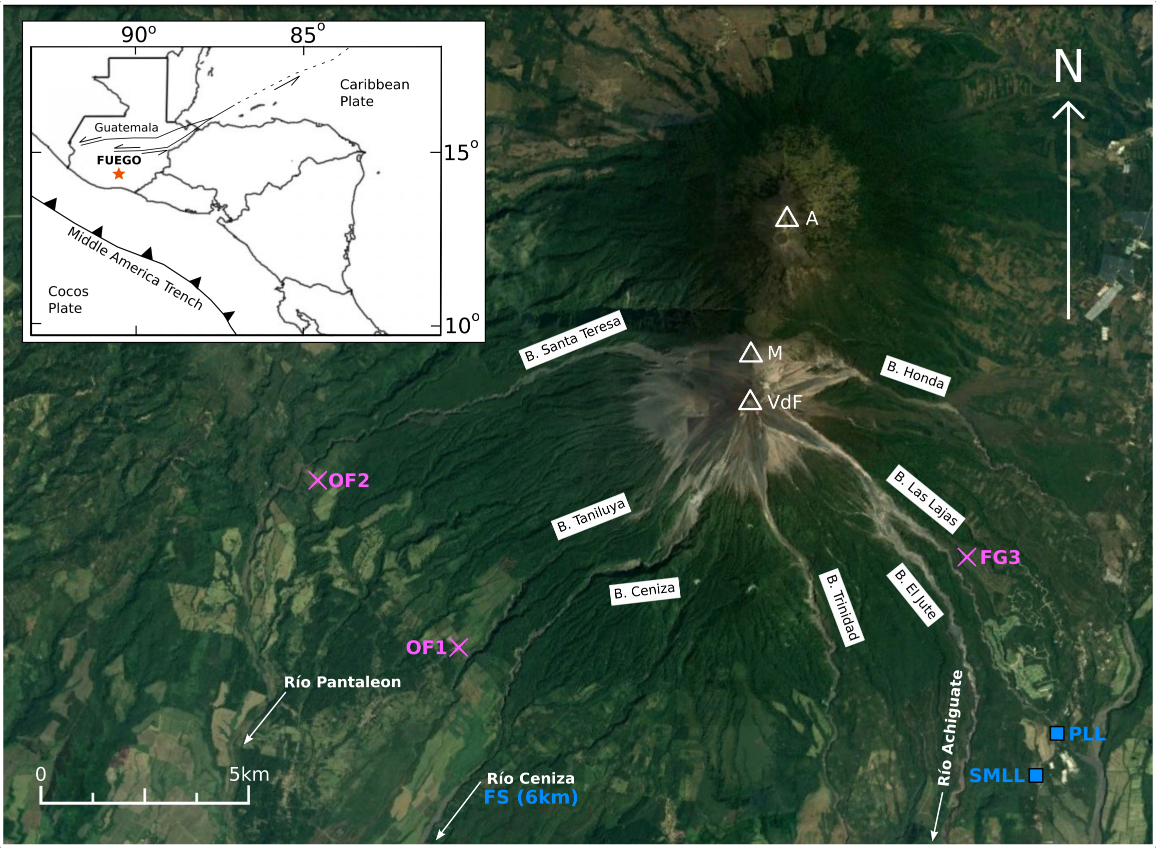

FIGURE 2.1. Map of Volcán de Fuego including its seven barrancas (drainage ravines) and major ríos (rivers), with (inset) location of Fuego within Guatemala. Barrancas of Fuego control movement of lava flows, pyroclastic flows, and lahars. Principal eruptive centres of the Fuego-Acatenango massif are (north to south) Volcán Acatenango (indicated as A), La Meseta (M) and Volcán de Fuego (VdF). INSIVUMEH's two Fuego observatories, OVFGO1 and OVFGO2, are located respectively in the villages of Panimaché Uno and Sangre de Cristo and are indicated by pink crosses. They are labelled as "OF1" and "OF2". INSIVUMEH's short-wave seismometer that provided RSAM data in Section 4 is labelled as "FG3" and indicated by a pink cross. Blue labels indicate the community of San Miguel Los Lotes (SMLL), the Las Lajas bridge (PLL), and the Scout encampment (FS), located approximately 6 km south of map's southern extent down Barranca Ceniza. Map data: Google, Digital Globe (2018).

which to closely compare their relative magnitudes. However, several details suggest that some of the earlier eruptions were at least equivalent in magnitude to those of 1974. An account of the eruption in January 1582, for instance, states "in the twenty four hours that the fury lasted, one couldn't see anything from the volcano but rivers of fire and very large rocks made embers, which came out of the volcanoes mouth and came down with enormous fury and impetus" [Ciudad Real, 1873]. This account of 24 hours of paroxysmal activity, including violent ejection of ballistics and possible pyroclastic flows, is comparable to some of the larger paroxysmal eruptions observed in Fuego's more recent eruptive history.

Records of the 1717 eruption are well-preserved and give a full chronology of the activity. The main phase of the eruption lasted between 27th and 29th August when locals heard rumbles and explosions from Fuego's summit. People reported glowing clouds and fiery phenomena, assumed to be pyroclastic flows [Hutchison et al., 2016]. On 29th September several earthquakes followed the eruption, in turn triggering mudflows apparently originating from nearby Volcán de Agua [Hutchison et al., 2016]. However, reports of damages to the communities of Mixtan and Masagua on the Río Guacalate, beyond the confluences of drainages from Fuego and Agua volcanoes, suggest that at least some of these mudflows originated from Fuego. An anonymous account of the eruption of 29th June 1880 states that people in Mazatenango and Retalhuleu had to write by artificial light, because of "dense darkness ... caused by a thick and continuous ash rain, thrown without a doubt by the volcano from whose eruption we have been talking about" [Feldman, 1993]. The cities of Mazatenango and Retalhuleu are 67.5 km and 85.9 km respectively from Fuego, showing the extensive tephra dispersal of the 1880 eruption.

An important account of the January 1932 eruption comes from Deger (1932). Strong earthquakes were felt on the morning of 21st January as far as Livingstone (on the Caribbean coast of Guatemala) and in neighbouring Honduras and El Salvador. The original eruption column was estimated at 17,000 ft asl (~ 5200 m). The episode generated an extremely large and long-ranging tephra blanket: fine ash fall was observed in many places throughout Guatemala, and close to Fuego the fall of clasts as large as pebbles and cobbles was reported [Deger, 1932]. The morphology of the summit crater was changed by the eruption, and its diameter greatly increased [Deger, 1932].

Fuego was particularly active in the 1970s. Eruptions in September 1971 and February 1973 were comparable in size to each of the individual eruptions composing the sub-Plinian eruptive episode of 1974 [Bonis and Salazar, 1973, Martin and Rose, 1981]. The eruption of 14th September 1971 was particularly impressive: a report from the Instituto Geográfico Nacional (IGN) states, "All observers agree this was the most spectacular eruption in memory (at least 70 years)" [Venzke, 2013]. The 1971 eruption began suddenly and lasted 12 hours, producing an eruptive column of 10,000 m asl and extensive pyroclastic flows [Bonis and Salazar, 1973]. Flows travelled E down Barranca Honda, but the direction of ash dispersal was W towards the departments of Acatenango and Yepocapa. Approximately one fifth of roofs in the town of San Pedro Yepocapa, 8 km W of Fuego, collapsed under the weight of ash fallen, estimated at 30 cm depth [Bonis and Salazar, 1973, Venzke, 2013]. The eruption of 1973 was longer but less powerful than that of 1971, although the flows produced in 1973 were both longer and more voluminous than in 1971 [Bonis and Salazar, 1973]. The majority of activity occurred between 22nd February and 3rd March 1973, producing pyroclastic flows on Fuego's SW, W and E flanks, and ash that was dispersed to a distance of 70 km [Bonis and Salazar, 1973, Venzke, 2013].

The 1971 and 1973 eruptions likely awakened both local and academic interest in Fuego's activity [Bonis and Salazar, 1973]. They may explain the wealth of academic literature on the sub-Plinian eruptive episode that occurred in October 1974, which is one of the most well-documented volcanic eruptions of Central America [Roggensack, 2001]. Between 10th and 23rd October 1974, Fuego produced four powerful eruptions that generated extensive tephra and multiple pyroclastic flows [Davies et al., 1978, Rose et al., 2008]. Tephra from Fuego again collapsed roofs in San Pedro Yepocapa and spread to the capital, [Ciudad de] Guatemala, located 40 km E of Fuego and then with a population of over a million [Vallance et al., 2001]. The most violent of these four eruptions began at 21:45 on 17th October, with an eruption that sustained a plume reaching >7 km above Fuego's summit (>11 km asl) [Rose et al., 1978]. No lava flows were produced in the October eruptive episode [Davies et al., 1978]. Instead, the fortnight of activity produced an extraordinary volume of tephra and pyroclastic flows that descended several of Fuego's barrancas, reaching a maximum of 8 km from the volcano's summit [Escobar Wolf, 2013]. Estimates of eruptive volume produced during the fortnight range from 0.2 km^3 of tephra (0.1 km^3 dense rock equivalent, DRE) [Rose et al., 1978], to 0.6 km^3 of tephra and glowing avalanche material [Davies et al., 1978].

The sub-Plinian eruption in 1974 was followed by several small eruptions of Fuego between 1975 and 1978 [Rose et al., 1978]. These eruptions were succeeded by two decades of quiescence (1979 – 1999), interrupted only briefly by small Strombolian eruptions in 1987 and 1988 [Andres et al., 1993]. The extended quiescence accounts for the relative dearth of literature published on Volcán de Fuego during this period.

Volcán de Fuego erupted again on 21st May 1999 with a VEI 2 eruption that produced pyroclastic flows and tephra fall [Lyons and Waite, 2011]. Fuego's eruptive activity since 1999 has been dominated by open-vent conditions producing Strombolian activity, summit explosions, persistent degassing, and lava flows (Figure 2.3). However, between 1999 and 2012, with a hiatus between the years 2008 and 2011, Fuego also consistently produced several eruptive events each year that were of greater energy and duration than typical Strombolian behaviour [INSIVUMEH, 2012b]. These events are referred to by INSIVUMEH as "paroxysms" or "paroxysmal eruptions", and these terms will be used throughout this thesis. The definition of a "paroxysm" or "paroxysmal eruption" at Volcán de Fuego is based on a group of characteristics shared by these events that have occurred since 1999 and been classified in previous literature [Lyons et al., 2010]. In agreement with previous authors, this thesis defines a paroxysmal eruption at Fuego as an above-background eruptive event consisting of a three-stage process: (i) a waxing phase, involving effusion of lava flows and an increase in frequency and energy of intermittent gas chugging and Strombolian explosions at summit, persisting for 24 – 48 hours; preceding (ii) a climax in explosive activity, the "paroxysm" itself, involving maintained effusion of lava flows and

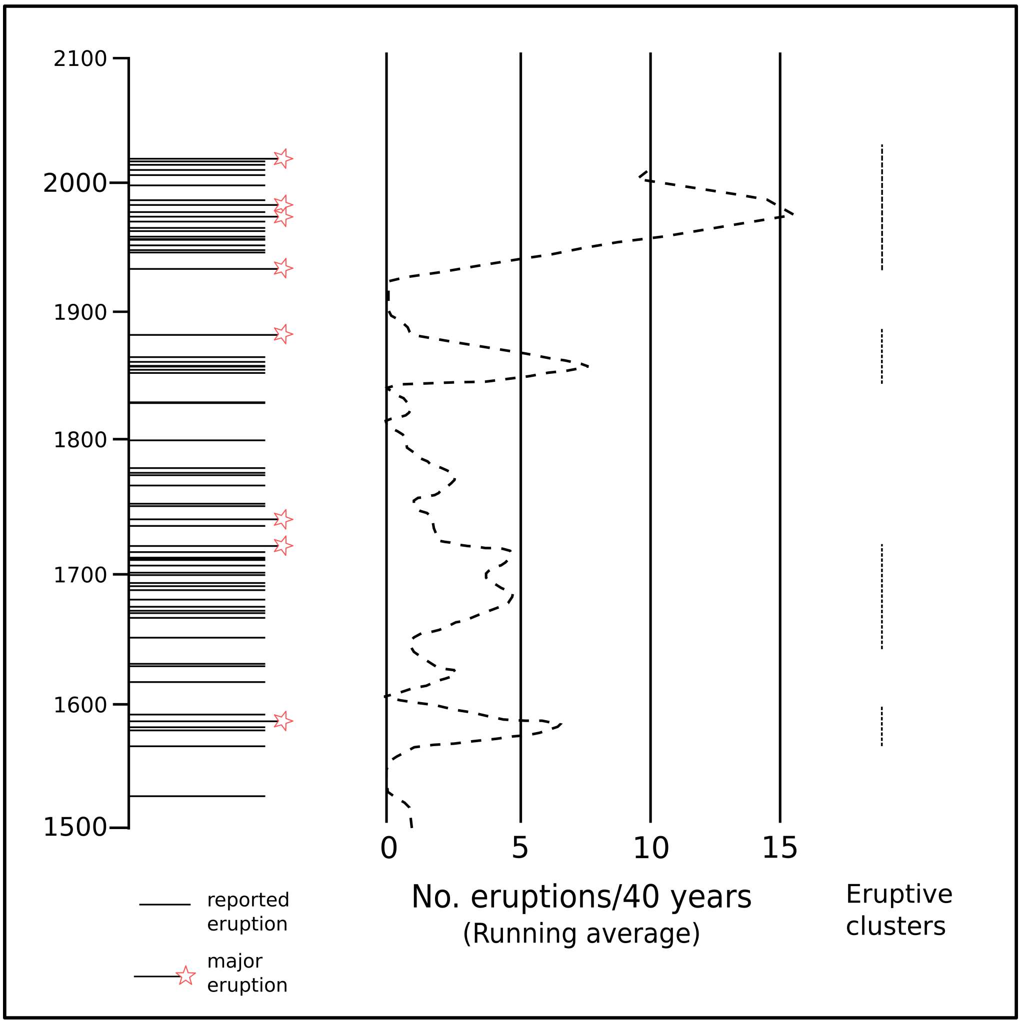

FIGURE 2.2. Historic activity of Fuego since 1524. Four eruptive clusters of 20 – 70 years have defined the eruptive history of Fuego since 1524. Significant eruptions in 1581-2, 1717, 1737, 1880, 1932, 1971, 1974, 1999 and 2018 have been highlighted by red stars. Modified from Rose et al. (1978) via Vallance et al. (2001) and GVP (2018).

continuous explosions sustaining an eruptive plume of fine ash and gas, with intermittent production of pyroclastic flows; succeeded by (iii) a subsequent waning of activity [Lyons et al., 2010]. A good example of a paroxysmal eruption at Fuego is the description of the 13th September 2012 eruption found in the preliminary report released by INSIVUMEH [INSIVUMEH, 2012a].

Some of Fuego's paroxysms have caused significant disruption to surrounding communities. For instance, between January and August 2003, several communities were evacuated due to eruptive activity of Fuego, activity that included a paroxysmal eruption in January [Webley et al., 2008]. Several paroxysmal events between 1999 and 2012 have been deemed significant by INSIVUMEH due to the greater volume of fine ash and pyroclastic flows they generated:

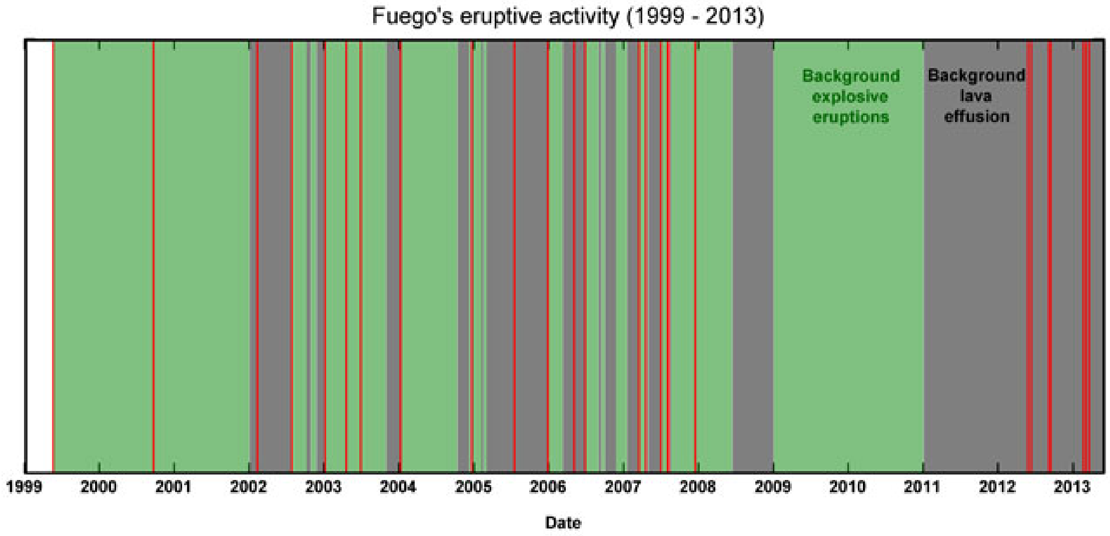

FIGURE 2.3. Time-series illustrating activity of Fuego between 1999 and 2013, with colour bars representing different eruption styles. Activity in early 2000s and 2009 – 2011 was dominated by background explosive eruptions (green), while background effusive activity dominated between 2005 – 2007 and 2011 – 2013 (grey). Episodes of significantly above-background explosive activity (paroxysms) illustrated in red. From GVP (2018), originally by Rüdiger Escobar-Wolf.

21st May 1999; 9th February 2002; 8th January 2003; 29th June 2003 (which completely filled Barranca Santa Teresa with pyroclastic flow deposits); 16th – 18th July 2005 (~10 A.J.); 5th – 8th May 2006; 7th – 9th August 2007; 15th December 2007; 13th September 2012; and 3rd June 2018 (INSIVUMEH, 2012). (For a complete list of notable (VEI ≥ 2) eruptive events at Fuego between 1524 – 2018, please refer to Appendix B (Chapter 7).) Consistent monitoring between 2005 and 2007 revealed patterns in eruptive behaviour that tracked well with radiant heat output from MODIS and seismic RSAM values [Lyons et al., 2010]. During these three years Volcán de Fuego displayed a cyclical pattern of behaviour consisting of three stages: (i) passive lava effusion and minor Strombolian explosions; (ii) paroxysmal eruptions involving a sustained eruption column and rapid lava effusion; (iii) passive degassing without lava effusion [Lyons et al., 2007, 2010]. Multi-instrumental investigation of Fuego's activity between 2008 and 2009 revealed the presence of two summit crater vents, each associated with distinct styles of explosive activity. The primary central summit vent produced impulsive, powerful, ash- and bomb-rich explosions interspersed with periods of ash-free gas puffing, while a secondary vent 100 m W of the summit produced long-duration, emergent, ash-rich explosions [Nadeau et al., 2011, Waite et al., 2013]. Throughout this observation period, a large variety of explosion intensities were observed. However, the largest explosions were all associated with very long period (VLP) seismic activity and showed evidence for pressurization of the upper conduit under a crystallized plug prior to explosive release [Lyons and Waite, 2011, Waite et al., 2013]. More recently, detailed analysis of VLP signals has provided a means to distinguish eruptive styles at Fuego [Waite et al., 2013].

One of Fuego's largest eruptions in the period 1999 – present occurred on 13th September 2012 [BBC, 2012]. 48 hours before eruption, an increase in long-period (LP) events was recorded, along with the appearance of a large-amplitude volcanic tremor. During this time, activity produced a 300 m lava flow on Fuego's southern flanks. Due to the increase in activity, a special bulletin was issued to Guatemala's national emergency response and disaster risk reduction agency, CONRED [INSIVUMEH, 2012a]. The eruption began at 04:00 local time on 13th September and by 07:15 an eruption column had risen 2000 m above the summit crater, causing CONRED to issue first a yellow alert ("prepare to act") and subsequently an amber alert ("evacuate if necessary") (for more detail on CONRED's alert system, see Chapter 3 Section 3.3). Pyroclastic flows descended the southern flanks at 09:12 and CONRED escalated the alert level to the highest, red, status ("evacuate immediately") [INSIVUMEH, 2012a].

More recently, a large paroxysmal eruption of Fuego occurred on 3rd June 2018. The eruption began at 06:00 local time with powerful incandescent fountaining and a tall eruptive column. During the morning hours, pyroclastic flows descended the W flanks of Fuego. The eruption in its initial progress appeared to be a "typical" paroxysm [Pardini et al., 2019]. However, beginning at 12:00, the intensity of the paroxysm increased, and the direction of tephra dispersal and pyroclastic flow descent shifted towards the SE. Between 14:00 and 16:00, a series of pyroclastic flows descended Barranca Las Lajas, destroying a bridge and a community and causing the deaths of several hundred people [SE-CONRED, 2018]. This eruption remains the greatest in terms of human impact within Fuego's extended history.

2.4 Methods

2.4.1 Volcanic Radiative Power from MODIS-MIROVA

Thermal activity of Volcán de Fuego has been obtained by using MIROVA, an automatic volcanic-hotspot detection system based on the analysis of MODIS infrared data [Coppola et al., 2016]. MODIS (MODerate resolution Imaging Spectroradiometer) is a multispectral spectroradiometer carried on board of Terra and Aqua NASA's satellites (launched on polar sun-synchronous orbit on March 2000 and May 2002, respectively). Each MODIS sensor scans the globe surface twice a day (one at night and one during the day), and collects radiance data on 36 spectral bands spanning from 0.4 to 14.4 μm. By using Middle Infrared (MIR) data acquired by MODIS, MIROVA completes automatic detection and location of high-temperature thermal anomalies and provides a quantification of the Volcanic Radiative Power (VRP) within 1 to 4 hours of each satellite overpass (`www.mirovaweb.it`). Night-time MODIS level 1b data of Fuego were used to produce the results presented in this chapter. Processing of satellite images occurs in six stages: (1)

removal of a 'bow–tie effect' associated with high scan angles, (2) resampling of original 1b data to produce a normalized thermal index (NTI) map, (3) hotspot detection of apparently thermal-anomalous pixels, (4) calculation of the apparent anomaly at 4μm(ΔL_{4STR}), (5) subtraction of a residual background to estimate of L_4VOLC, and (6) estimation of the volcanic radiative power (VRP). In (2), original MODIS level 1b granules are resampled into an equally-spaced 1 km grid (Universal Transverse Mercator System - UTM) and cropped within a 50 x 50 km mask centred over the target volcano summit to produce a NTI map. Hotspot detection is achieved by identification of pixels that 'may' or 'certainly' show a thermal anomaly relative to the NTI map produced in (2). Pixels that satisfy the condition $NTI_{PIX} > NTI_{Thresh}$ are flagged as anomalous. Calculation of the apparent anomaly is achieved by subtracting the background radiance at 4μm from the radiance of alerted pixel(s) at 4μm. Variation in background radiance caused by cloud is controlled for by the single condition $BT_{12} < 265$ K (where BT_{12} is the brightness temperature at 12μm); pixels that satisfy this condition are flagged as cloudy. Estimation of L_4VOLC is achieved by comparison of results of (4) with a background of similar topography and assumed inactivity (see Coppola et al. [2016] for details). Finally, VRP values are retrieved from the net spectral radiance at 4μm using the equation in Wooster et al. [2003]:

$$VRP = 1.89 * 10^7 * (L_{4H} - L_{4bk}) = 1.89 * 10^7 * L_{4VOLC}$$

where L_{4H} and L_{4bk} are the 4μm radiances of, respectively, hotspot-contaminated pixels and background pixels. These correspond to the net spectral radiance at 4μm, L_{4VOLC}. The Wooster equation allows estimations of VRP (± 30%) from hot surfaces having temperatures ranging from 600 - 1500 K. Between March 2000 and July 2018 MODIS acquired 11639 night-time images over Volcán de Fuego. 4132 of these 11639 images (~35%) triggered the MIROVA hotspot detection algorithm, indicating consistent anomalous highs in thermal emission throughout the analysed period.

2.4.2 Statistical detection of a new eruptive regime

Following the methods of Coppola et al. [2012], a rank-ordered statistical plot of all MIROVA night-time values between January 2000 and June 2018 (n = 4412) compares the populations for Fuego between 2000 – 2014 and 2015 – 2018 (Figure 2.4 (a)). A subset of data with VRP <1 MW is related to overpasses during cloudy conditions or under extreme viewing geometries, either of which impede detection of a clear thermal anomaly. A small true thermal anomaly occurring within this subset would be impossible to distinguish from noise; therefore, we have excluded values <1 MW (illustrated by dashed line in Figure 2.4 (a)).

In agreement with Coppola et al. [2012], a set of values approximating a linear trend would constitute a group of events with similar characteristics; thus, two distinct linear trends in the Stromboli MIROVA dataset illustrate a shift between Strombolian and effusive eruptive regimes.

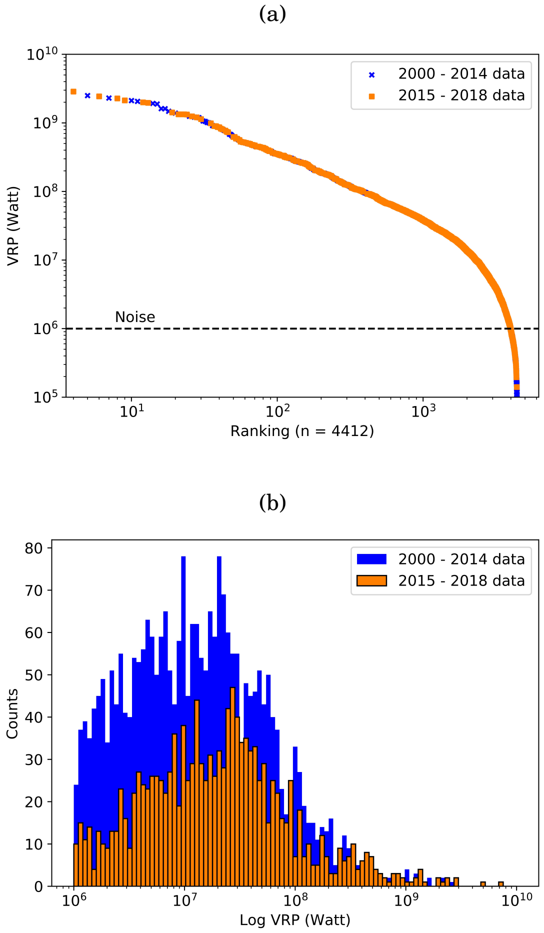

FIGURE 2.4. (a) rank-order plot for night-time MIROVA values between January 2000 and June 2018 (n = 4412). (b) histogram of two population groups (2000 - 2014 in blue, 2015 - 2018 in orange). Greater number of larger VRP values in 2015 - 2018 dataset illustrated by skew of data towards the right of the plot.

In the Fuego dataset, by contrast, a gradual shift in linear trend occurs between 1 x 106 and 3 x 107 MW of VRP. There is no clear distinction between the datasets of 2000 – 2014 and 2015 – 2018 (Figure 2.4 (a)), likely because both contain periods of Strombolian activity, lava effusion, and paroxysmal eruptions. However, plotting the frequency distributions of the two datasets (Figure 2.4 (b)) shows apparent differences that can be confirmed with simple statistical analysis. MIROVA night-time data between 2000 and 2014 have values between 0.001 MW and 2509 MW, and an arithmetic mean of 37.94 MW (variance 1.85 x 1016), while values between 2015 and 2018 fall between 0.0008 MW and 6974 MW and have an arithmetic mean of 77.61 MW (variance 9.79 x 1016). Applying a two-sided T-test to the populations indicates the difference in population statistics, with a t-statistic value of 4.58 and a p-value of 5.02 x 10-6. Using the standard threshold of significance (α-value of 0.05), we can reject the null hypothesis that the

2000 – 2014 and 2015 – 2018 datasets are of the same distribution, and therefore state that night-time MIROVA values reveal a new eruptive regime beginning at Fuego in January 2015.

2.4.3 Correlating MIROVA with other data streams

Lyons et al. [2010] combined ground observations with radiative power values and lava flow lengths determined from MODIS observations to reveal a repeating pattern of passive lava effusion, followed by paroxysm then degassing explosions, at Fuego between 2005 and 2007. We use similar methods to present evidence that a new pattern of eruptive activity at Fuego began in January 2015, characterized by an increase in paroxysmal eruptions (both in frequency and in total energy), observable by changes in radiative power values. In order to study the new eruptive regime in greater detail, analysis was performed on a more comprehensive MIROVA dataset of Fuego from 2015 – 2018 that includes VRP values obtained from daytime MODIS data. A threshold of 200 MW[1] has been chosen to investigate the largest eruptions as this threshold (1) yields 166 above-threshold VRP values, and therefore provides a reasonably small dataset to study in detail; and (2) is extremely well-correlated with visual observations of above-background activity as recorded by special bulletins created and disseminated by INSIVUMEH. These bulletins document any occurrences of above-background activity of Fuego, and contain details of eruptive behaviour derived primarily from visual observations from OVFGO1 (for location, see Figure 2.1). This documentation includes specific reporting of paroxysmal onset between 2015 and 2018. For this chapter, paroxysm onset time is defined as the local time recorded by the INSIVUMEH special bulletin that first reports a paroxysm. However, the details of defining onset of a paroxysmal eruption are worthy of scrutiny and are discussed further in Chapter 4. INSIVUMEH determines paroxysmal onset by a number of parameters, including a steep relative increase in RSAM and observations of above-background activity (e.g., elevated number of summit explosions per hour, energetic lava fountaining) reported from OVFGO1 and OVFGO2. Several other monitoring parameters, including Washington VAAC reports and daily RSAM values derived from INSIVUMEH's primary seismometer on Fuego (FG3), also correspond to periods of above-background activity in 2015 – 2018. The significance of correlation between these datasets is discussed in Section 2.6.

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[1] A magmatic source (1000°C) with diameter 42 m is required to produce a VRP of 200 MW.

2.5 Results: changes in activity since 2015

2.5.1 Satellite observations of 21st-century (2000 - 2018) and recent (2015 - 2018) activity)

A time-series of MIROVA[2] night-time data of Volcán de Fuego between January 2000 and June 2018 traces the activity of the volcano throughout the 21st century (Figure 2.5). Several features are notable: the occurrence of occasional high-magnitude VRP values (≥1000 MW) between 2002 and 2007, on the order of 1 – 2 per year; the disappearance of such values between 2008 and early 2012; and the appearance, from early 2015, of ≥1000 MW values at considerably greater frequency than those appearing in 2002 – 2007 (all Figure 2.5a). These large-magnitude VRP values represent a series of closely-spaced, short-lived periods of high thermal radiation. VRP values for Fuego are not temporally consistent, but cumulative radiative energy (CRE) values for the entire period 2000 – 2018 can be derived by resampling VRP values to daily and weekly means, multiplying by daily or weekly time, and plotting the resulting cumulative values (Figure 2.5b). A total CRE value of 1.70 x 1016 J (from daily mean) or 1.91 x 1016 J (from weekly mean) is found for Fuego from 2000 – 2018. Remarkably, almost half of this value is generated in the period 2015 – 2018 (7.25 x 1015 J for daily mean, 8.32 x 1015 J for weekly mean; see Figure 2.5b).

A comparison of VRP values between (1) 2000 – 2018 and (2) 2015 – 2018 illustrates in further detail the increase both in frequency and in relative amplitude of large-magnitude VRP values beginning in January 2015 (Figure 2.6). Although large-magnitude VRP values occur prior to 2015, they occur less frequently (217 values ≥1000 MW between 2000 and 2014 compared to 169 between 2015 and 2018). The largest VRP value to occur before 2015 is 2508 MW, on 16th March 2007; after 2015 is 6974 MW, occurring on 29th July 2016. Both of these values are associated with paroxysmal eruptions of Fuego and recorded by INSIVUMEH, as discussed later in this chapter (see Section 2.5.2). The highest-magnitude peaks observed post-2015 do not always coincide with the largest paroxysmal eruption: the eruptions of 3rd June 2018 and 5th May 2017 are considered to be two of the largest since 1999, yet they are accompanied by relatively small thermal peaks.

The guiding study by Coppola et al. [2012] performed on MIROVA data from Stromboli between 2000 and 2011 stated that >90% of values in their dataset are <1 MW and can be excluded from analysis, as they are associated with overpasses taken during cloudy conditions, or at high angles. Exclusion of images could be justified by comparison to images from other satellites (e.g., LandSat). Although cloud cover is common at Fuego, MIROVA values from 2000 to 2018 are of noticeably greater value than from Stromboli: 3975 of 4412 (90.1%) VRP values are >1 MW, and 386 values (8.75%) are >100 MW, highlighting the remarkable radiative energy that Fuego has been emitting in recent years.

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[2] to the authors' knowledge, there have been no changes between 2000 and 2018 in the MODIS sensors that provide the data for MIROVA.

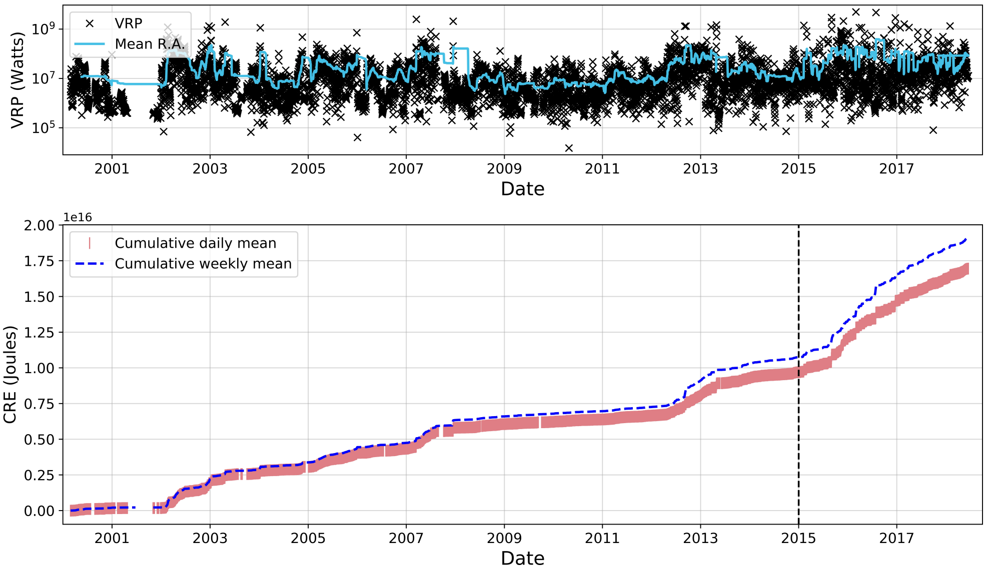

FIGURE 2.5. Night-time VRP values from MIROVA track changes in activity at Volcán de Fuego throughout the period 2000 – 2018 (black crosses). A mean running average is illustrated by a solid blue line (annotated as 'Mean R.A.' (Figure 2.5a, above)). Taking daily and weekly averages of VRP values allows for calculation of CRE emitted by Fuego throughout the period, as seen in Figure 2.5b (below). Almost half of total CRE generated by Fuego in the period 2000 – 2018 was generated after 2015, as illustrated by dashed vertical line. Data sourced from `www.mirovaweb.it`.

2.5.2 Correlating recent MIROVA observations with other data streams

The most informative and consistent data stream available against which to compare MIROVA values is the archive of special bulletins produced by INSIVUMEH during elevated activity. In the case of Volcán de Fuego, special bulletins are generated to report on the progress of a paroxysmal eruption, of lava effusion, or on descent of pyroclastic flows or of lahars. The correlation between large-magnitude VRP values and INSIVUMEH bulletins that report on paroxysmal eruptions is extremely strong (Figure 7). According to INSIVUMEH, 12 paroxysms occurred in 2015, 15 in 2016, 12 in 2017, and two in the first half of 2018 ([Venzke, 2013]; Table 2.1). Of the 166 occurrences of VRP values >200 MW between January 2015 and June 2018, 141 (84.9%) correlate to a paroxysmal eruption, where a VRP value is considered to be correlated to a paroxysm if it occurs within ±48 hours of its onset. Of these 141 VRP values, 106 (75.1%) occurred at 0 – 48 hours after paroxysm onset. Choosing 200 MW as a threshold means that there are no paroxysmal eruptions not accompanied by an above-threshold VRP value (i.e., no false negatives). However, 13 anomalies appear, i.e., above-threshold VRP values not associated with a paroxysmal eruption. These 13 anomalies occur in five clusters of time representing four distinct eruptive events: in 2015 (11th May; 27th September); and 2018 (16th April; 12th May;

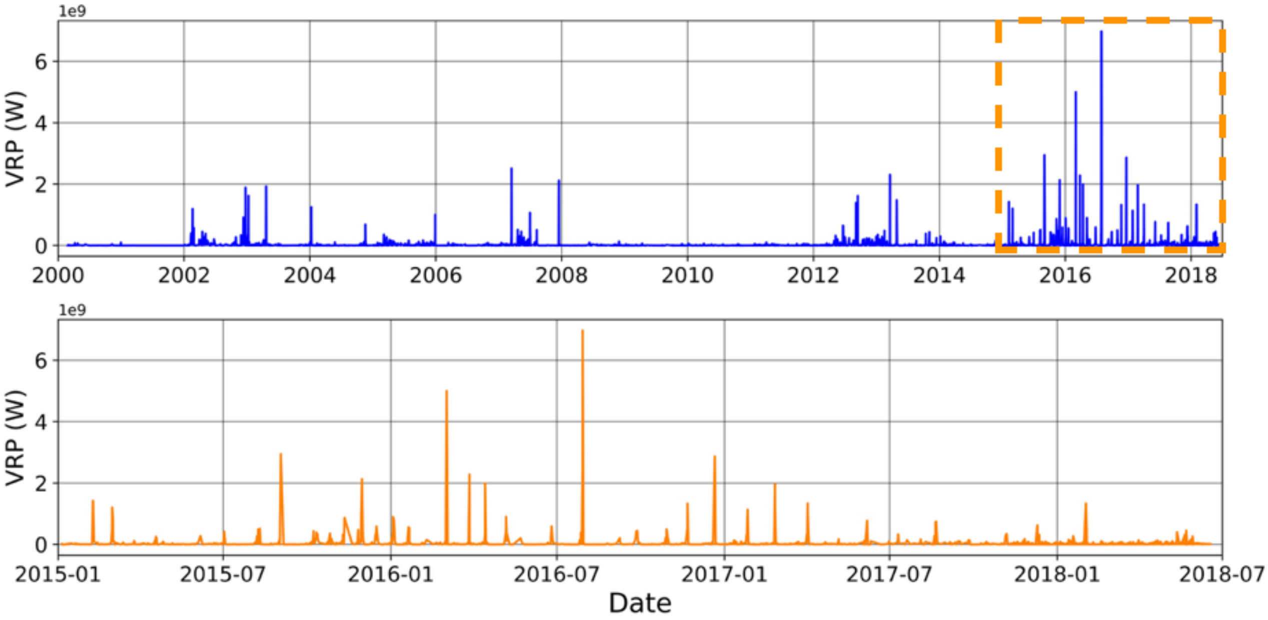

FIGURE 2.6. (above) Night-time VRP values from MIROVA track changes in activity at Volcán de Fuego throughout the period 2000 - 2018. Occasional peaks coincide with paroxysmal eruptions reported by INSIVUMEH (see Chapter 4). (below) Marked increase in the frequency of large-magnitude VRP values occurs in 2015, with appearance of first short-lived thermal radiation peak on January 5th, 2015.

21st May). A manual study of the MODIS images associated with these values shows they are real volcanogenic thermal anomalies i.e., they represent periods of elevated thermal activity at Fuego's summit. INSIVUMEH reported high activity including ash-rich explosions between 21st – 26th May 2015, and again between 30th September and 1st October 2015, accompanied by incandescent fountaining, and avalanches and lava flows in Barrancas Santa Teresa and Trinidad. Nevertheless, a paroxysm did not follow. INSIVUMEH reported increased activity at Volcán de Fuego on 16th April 2018, with increased explosive activity and effusion of a 1300 m lava flow in Barranca Santa Teresa, although this was not followed by a paroxysmal eruption. The thermal anomalies of 12th and 21st May 2018 are connected in the same period of above-background activity. Fuego was moderately active on 12th May, generating frequent ash-rich explosions and incandescent fountaining from its summit. Lava effusion towards Barranca Ceniza began on 14th May, continuing until at least 21st May, when the flow had reached a length of 700 – 800 m. On this occasion the lava flow was not a precursor to paroxysmal eruption, as activity decreased and the flow stopped by 26th May.

Year	Date	No.	Max VRP (MW)	Bull no.	Lava	Inc	A	PF	Lm	LL (m)	EC (m)
2015	07/02/2015	1	1423.30	008, 015	X			X		1000	4300
	01/03/2015	2	1206.00	025	X	X				1600	5000
	18/04/2015	3	410.38	025	X	X				600	4800
	05/06/2015	4	277.92	033	X	X				1200	5000
	01/07/2015	5	3756.63	054, 055	X			X		1500	4500
	09/08/2015	6	2728.50	058, 059	X	X	X			3000	4700
	01/09/2015	7	2444.30	065, 070	X	X			X	800	5000
	10/10/2015	8	386.73	082	X	X			X	1200	4600
	26/10/2015	9	357.01	087	X			X	X	1500	4700
	09/11/2015	10	429.15	091	X	X			X	1800	5000
	30/11/2015	11	2132.39	101	X	X		X	X	3000	6000
	15/12/2015	12	338.57	105	X					800	4700
2016	03/01/2016	13	1220.44	004	X				X	3000	7300
	19/01/2016	14	563.63	008, 009	X	X		X	X	3000	6500
	10/02/2016	15	6126.95	024, 026	X	X	X	X	X	2000	5000
	01/03/2016	16	4998.34	031, 034	X		X			700	6000
	26/03/2016	17	2277.54	045	X				X	2000	6000
	13/04/2016	18	1993.77		X					2000	4800
	06/05/2016	19	1460.81		X	X	X		X	3000	5500
	22/05/2016	20	476.61	097, 099	X				X	1500	5000
	24/06/2016	21	347.75	114	X	X	X		X	2000	4800
	28/07/2016	22	2442.92	138	X	X	X	X	X	3000	5500
	07/09/2016	23	587.13	169, 171	X	X	X		X	1800	4900
	27/09/2016	24	517.99	180, 182	X	X	X		X	3500	4800
	29/10/2016	25	4279.08	189	X	X	X		X	1300	7000
	20/11/2016	26	1597.19	201	X	X	X		X	2500	5000
	20/12/2016	27	2866.18	210, 212	X	X	X	X	X	2000	5000
2017	26/01/2017	28	1222.48	004, 009	X	X	X	X	X	900	4800
	25/02/2017	29	1962.73	020	X	X	X			1600	5000
	01/04/2017	30	2531.27	034	X					2000	4800
	05/05/2017	31	423.56	046	X	X		X	X	2000	6000
	06/06/2017	32	774.13	068	X	X	X	X		500	6000
	11/07/2017	33	4782.65	096, 097	X	X				2300	5000
	07/08/2017	34	295.31	105	X	X	X			1300	4900
	21/08/2017	35	742.79	127	X				X	1400	5500
	13/09/2017	36	1733.03	148	X	X	X		X	500	4500
	28/09/2017	37	713.82	154, 157	X	X				600	4800
	05/11/2017	38	443.22	166, 170	X		X		X	1200	4800
	10/12/2017	39	1766.86	182, 187	X	X	X		X	1500	5000
2018	31/01/2018	40	1334.75	005, 011	X	X	X	X	X	800	4800
	03/06/2018	41	242.17	027, 028			X	X	X		10000

Table 2.1: Table of all paroxysms at Fuego, January 2015 to June 2018. Max VRP gives maximum VRP value associated with paroxysm (±48 hours). Bulletin no. gives specific INSIVUMEH special bulletin in that year related to paroxysm (e.g., 004 for 2016 refers to bulletin #004-2016). Lava, Inc, A, PF, Lm refer to eruptive phenomena reported in special bulletins (respectively: lava, incandescent fountaining, avalanche, pyroclastic flow, and degassing sounds "like a locomotive train"). LL and EC refer to maximum lava flow length and eruptive column height (asl) recorded in any special bulletin associated with that paroxysm. Note that paroxysm may produce several lava flows; values stated here are only of single longest flow. For full table including details of all VRP values >200 MW Jan 2015 – Jun 2018 (n = 166), see Appendix C (Chapter 8).

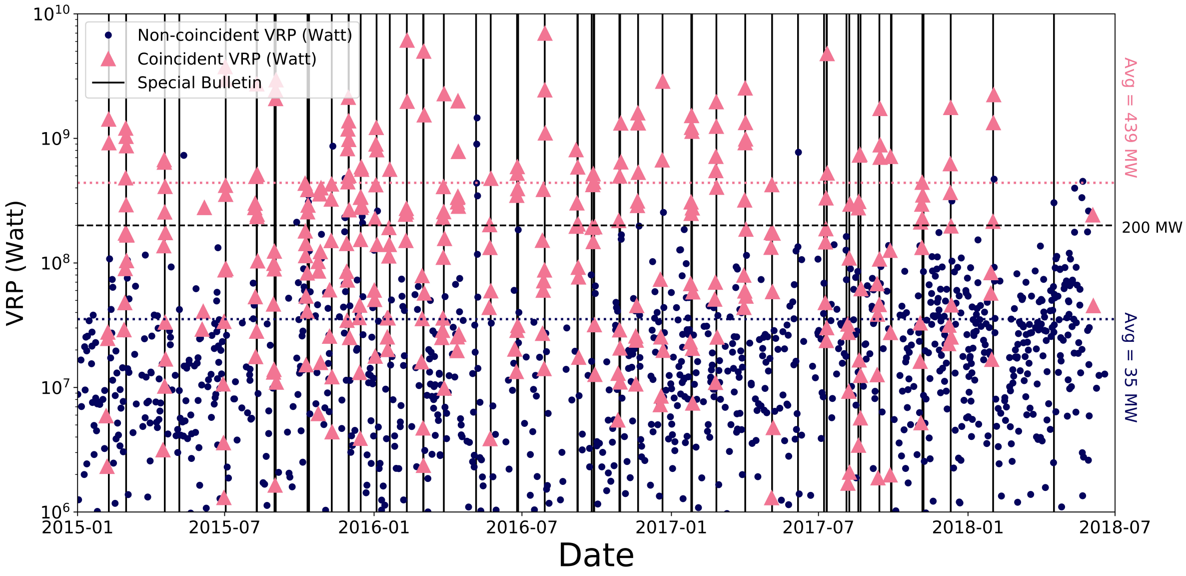

FIGURE 2.7. Plot of all night-time VRP values from MIROVA and INSIVUMEH special bulletins between January 2015 and June 2018. Pink triangles represent VRP values coincident (±48 hours) with INSIVUMEH bulletins (black vertical lines), while blue dots represent VRP values that occur more than 48 hours before/after a special bulletin. Dashed black line represents threshold of 200 MW, above which all paroxysmal eruptions are associated with at least one VRP value. Dotted pink and blue lines represent average of all coincident and non-coincident MIROVA values (439.47 MW and 35.37 MW, respectively).

Table 2.1 describes all paroxysmal eruptions between January 2015 and June 2018 and gives maximum VRP values associated with them, as well as occurrences of particular eruptive activity phenomena. An expanded version of Table 2.1, including a full description of eruptive activity contained in INSIVUMEH special bulletins, can be found in Appendix C (Chapter 8).

From Table 2.1, we can recognize certain features that are typically associated with a paroxysmal eruption of Fuego between 2015 and 2018. In the days before a paroxysmal eruption, explosive activity at the summit increases in frequency and intensity, and audible degassing noises reminiscent of a steam locomotive can be heard [Lyons et al., 2010, Ruiz and Manzanillas, 2011]. Eruptive behaviour evolves with more frequent audible degassing and more frequent and ash-rich summit explosions. The majority of paroxysmal eruptions (28 of 41, 68.2%) were reported to produce an incandescent fountain of several hundred metres above the summit crater. 40 of 41 (97.6%) paroxysms were accompanied by the effusion of lava flows in one or several of Fuego's barrancas. Of the bulletins that report both lava flows and incandescent lava fountaining, the majority state explicitly that lava flows are fed by the lava fountaining. All special bulletins reporting the onset of a paroxysmal eruption of Fuego explicitly state the estimated length of

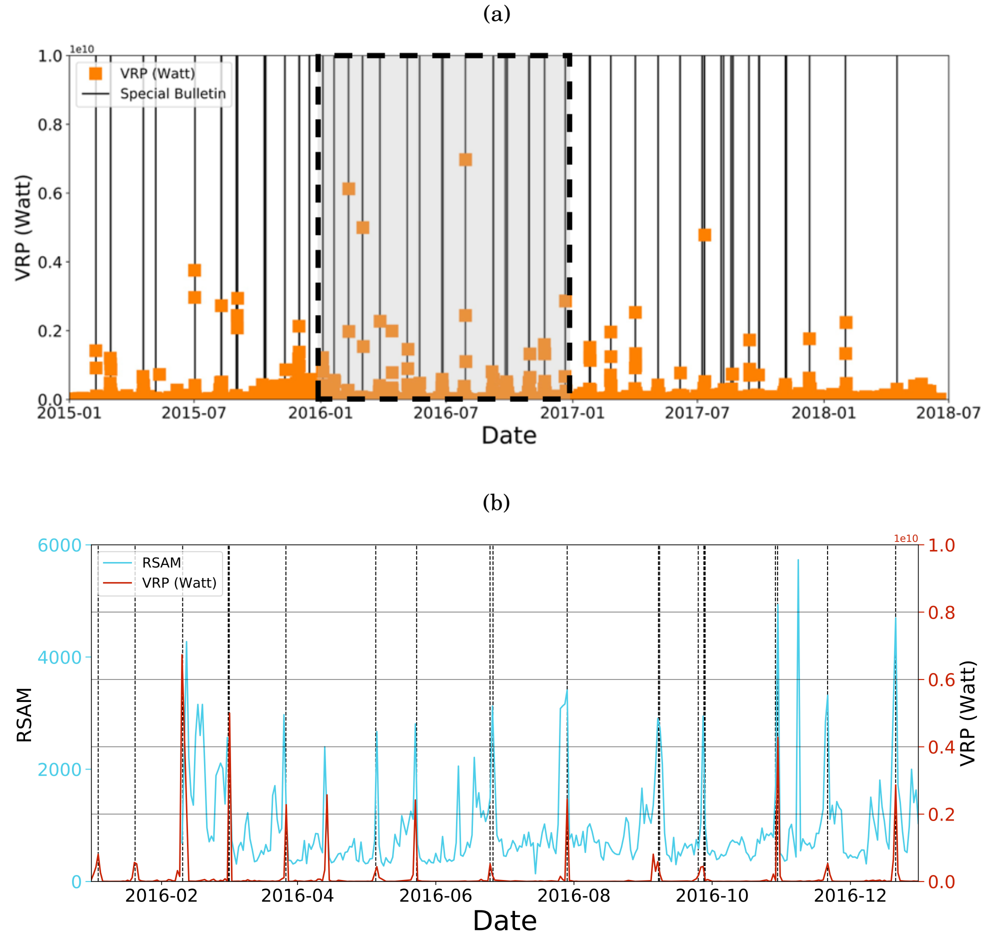

FIGURE 2.8. (Above) Plot of MIROVA values January 2015 – June 2018; y-axis is between 106 and 1010 W, to filter out low values associated with high angles or adverse viewing conditions. Vertical black lines show timings of all paroxysmal eruptions between 2015 – 2018 identified by INSIVUMEH through special bulletins. (Below) a subset of above plot, showing time-series of daily RSAM values (blue) against VRP values (red) derived from FG3 measurements. Timings of paroxysmal eruptions reported in INSIVUMEH special bulletins are plotted as dashed lines.

discharged lava flows, thus showing that lava flow effusion is a consistent precursor to paroxysmal eruption between January 2015 and June 2018. Lava flows associated with a paroxysm may achieve up to 3000 m in length. There does not appear to be a simple correlation between maximum lava flow length and maximum VRP value in paroxysms during this time. However, it should be noted that paroxysms at Fuego frequently produce several simultaneous lava flows in different barrancas, which is not illustrated by the Max lava length column (which records only the single longest lava flow of a paroxysm) so the lack of relationship between Max VRP value and Max lava length may be superficial only.

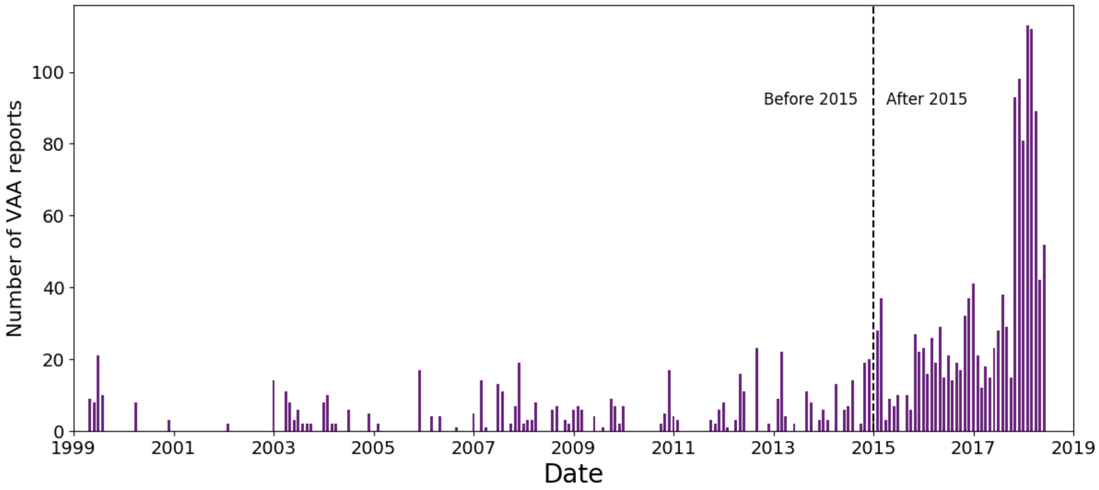

FIGURE 2.9. Evidence for new cycle of activity illustrated by number of monthly ash advisory reports generated by Washington VAAC between January 1999 and June 2018. Dashed line indicates boundary between period of moderate activity 1999 – 2014 and period of elevated activity beginning January 2015.

The appearance of short-lived, high-energy thermal peaks in the MIROVA night-time database of 2015 – 2018 can clearly be found in various other datasets that trace eruptive activity at Volcán de Fuego. For instance, frequent peaks in RSAM correlate closely with paroxysmal eruptions (Figure 2.8(a)). Indeed, RSAM is a primary monitoring method for INSIVUMEH to assess the possibility of imminent paroxysmal activity at Fuego (for more detail, see Chapter 4). The number of VAA reports generated monthly by the Washington Volcanic Ash Advisory Centre (VAAC) increases noticeably after January 2015 (Figure 2.9). Figure 2.9 shows the number of VAAs generated per month since the reawakening of Fuego in 1999. Of a total of 1932 VAAs generated between January 1999 and June 2018, over half (1352, 70.0%) were released between January 2015 and June 2018. A noticeable increase can be seen in the early period; for instance, the number of average monthly number of reports in 2014 was 7.5, compared to 13.7 in 2015 or 22.3 in 2016. However, it should be noted that this increase is unlikely to be due solely to increase in Fuego's activity. The Washington VAAC issue forecasts based on information from INSIVUMEH and pilots (among others), satellite data (including the GOES platform), and dispersion models. Factors causing the rise in monthly VAAC reports from Fuego since 2015 could include increased reporting from INSIVUMEH and/or pilots to the VAAC, and more frequent imagery available since the launch of GOES-16 in November 2016.

2.6 Discussion

2.6.1 Considering analogues: Explosive eruptions following lava effusion at other volcanoes

There are few other basaltic open-vent volcanoes where explosive eruptions consistently follow lava effusion in the style of Fuego's recent paroxysmal cycle. However, Llaima volcano in Chile displayed similar behaviour during an eruptive cycle in 2007 - 2009 [Romero Moyano et al., 2014]. The cycle included repeated lava effusion interspersed by more sporadic explosive eruptions with rapid onset and ending that were also characterized as "paroxysmal" [Franco et al., 2019]. Llaima is recognized as a good analogue to Fuego in a recent objective analogue identification method [Tierz et al., 2019]. Elsewhere, eruptions of Etna in 1995 – 1996 [Allard et al., 2006] and 2011 – 2012 [Viccaro et al., 2015, Calvari et al., 2018, Giacomoni et al., 2018] also bear some comparison to Fuego's recent activity. In the days before a paroxysmal eruption, the increase of summit explosive activity produces a satellite-detectable increase of thermal anomalies at Fuego's summit (in terms of both intensity and frequency). Similar increases are also observed before Etna's paroxysms as documented in D'aleo et al. [2019].

Sustained lava effusion preceding explosive paroxysm has been observed on multiple occasions at Stromboli [Polacci et al., 2009, Allard, 2010, Calvari et al., 2011]. In particular, Stromboli's eruptions in 2002 – 2003 and 2007 involved slow lava effusion before paroxysm, inspiring several models that may have application to Fuego; indeed, some authors cited the similarity between the two systems [Calvari et al., 2011]. Allard [2010] uses the collapsing foam model to explain the 2002 – 2003 and 2007 Strombolian paroxysms. Meanwhile, Calvari et al. [2011] interpret lava effusion during these periods as gradual decompression of Stromboli's magmatic system. The similar volume of lava erupted before each paroxysm (0.004 km^3) suggests that the trigger for paroxysm is the eruption of a critical volume of material. Gradual lava effusion acts to increase the depth of the bubble-rich magma column in the conduit, drawing up less-porphyritic, volatile-rich magma from a deeper storage zone into the upper system, where it rises through the conduit and erupts explosively (i.e., the paroxysm) [Calvari et al., 2011]. This model relies on several points of stability: of subsurface geometry, magma supply rate, and magma composition. A future avenue of exploration could be application of the Calvari et al. model to Fuego, by comparison of cumulative lava effusion volumes before individual paroxysmal eruptions. A discussion of how magmatic column height in Fuego's conduit may explain its paroxysms appears in Section 2.6.2.

Ripepe et al. [2017] focus on the same Strombolian paroxysms, with different conclusions. Persistent explosive activity does not fully clear the upper conduit, in which magma is stored and recycled. During pre-paroxysmal lava effusion, Ripepe et al. [2017] cited the increased contribution of a deep, volatile-rich magma that hampers magma recycling in the upper conduit; as lava effusion encourages the lower gas-rich source to rise through the conduit, the deep reservoir experiences fast decompression and further fuels the upper system with magma, eventually leading to paroxysm. This model changes the trigger of paroxysm from a perturbation at depth to changes in magmastatic conditions affecting decompression rate within the shallow subsurface. Invoking discharge from a shallow reservoir could explain the exceptional frequency of paroxysms seen at Fuego since 2015.

As complementary basaltic arc volcanoes, and for producing explosive paroxysms after sustained periods of lava flow effusion, there is merit in considering Stromboli, Etna, and Llaima as analogues with which to aid analysis of Fuego's behaviour. However, the paroxysmal eruptions that have occurred at Fuego since 2015 are extraordinary for both their consistency and their frequency. Furthermore, the crystal-poor magma produced by the Strombolian eruptions of 2002 – 2003 and 2007 is dissimilar to the strikingly crystal-rich of Fuego magmas (up to 40 – 50% phenocrysts in bombs erupted in 2017 – 18 pyroclastic flows (Hannah Moore, pers. comm.)). Nevertheless, there may be merit in applying the methods that produced the above models to Fuego's system. The installation of several broadband seismometers and an infrasound array at Fuego since the 3rd June 2018 eruption means that application of such methods is now possible.

2.6.2 Models for triggering paroxysms in Fuego

Lyons et al. [2010] propose two alternative models to explain a series of five paroxysmal eruptions observed at Fuego between 2005 and 2007. The first is the collapsing foam model introduced by Jaupart and Vergniolle [1989], where both effusive and explosive behaviours are caused by the accumulation, and subsequent release, of gas in an unstable foam layer. This hypothesis argues that lava effusion at surface is permitted by the accumulation of gas within a foam layer at a structural discontinuity in the magmatic subsurface. The eventual collapse of the foam layer into a gas slug that rises up the conduit drives Strombolian explosions and lava fountaining before the slug's arrival at surface. Such a model may produce similar behaviours to Fuego's if the viscosity or gas flux is high enough. The alternate hypothesis Lyons et al. [2010] propose for the trigger of Fuego's paroxysmal eruptions is the rise-speed dependent model advanced by Parfitt and Wilson [1995]. This model differentiates between low magma rise speeds, where bubbles coalesce into slugs and rise to produce classic Strombolian activity, with higher speeds, where the smaller differential between bubbles and their carrying body impedes bubble coalescence. The ascending magma-gas mixture thus achieves the fragmentation threshold necessary to produce runaway coalescence much deeper in the conduit [Parfitt and Wilson, 1995]. An increase in magma rise speed, therefore, would be the driving force behind the transition from effusive to explosive eruptive activity seen at Fuego. However, Lyons et al. [2010] observed an increase in paroxysmal frequency during 2007, that coupled with a decrease in lava output disagree with the implications of the rise-speed dependent model, where higher effusion rates should correlate with more paroxysmal eruptions. Both parameters have increased at Fuego since 2015.

As with observations from 2005 – 2007, Fuego's activity since 2015 has consistently included lava effusion prior to paroxysm. Detection of VRP values >200 MW clearly indicates the presence of hot magma at the surface, which may anticipate a period of sustained lava effusion, elevated explosive activity at the summit, or both. However, lava effusion does not guarantee that a paroxysm is imminent. Episodes of elevated activity in 27th September 2015, 16th April and 12th – 21st May 2018 generated lava flows but did not accelerate towards paroxysm. Compared to episodes of lava effusion that did culminate in paroxysm, these episodes are notable in producing lava flows of relatively minor length. Furthermore, effusion rates during these periods were relatively low: in May 2018, the lava flow grew 500 m in 48 hours (12th – 14th May), but effusion slowed with time, reaching 600 m on 18th May, and 700 – 800 m on 21st May. In comparison, episodes of lava flows culminating in paroxysm typically grow several kilometres in length within 48 hours of first appearance; for example, the paroxysm of 28th – 30th July 2016, where between 06:00 local time on 28th July and 14:30 on 29th July lava flows in Barrancas Santa Teresa and Las Lajas grew from 500 m and 1000 m to 3000 m each (see Appendix C (Chapter 8) for further information). This represents a significant increase in output from the paroxysms observed between 2005 and 2007, where similar flow lengths were achieved across months. It is also illustrated by the increase in cumulative energy seen in Figure 2.5. A possible explanation for this increase could be a rise of the magmatic column within Fuego's conduit, beginning in 2015 and maintained until 2018. This hypothesis has been proposed by Coppola et al. [2012] to explain the patterns in summit activity and effusive eruptions observed at Stromboli between 2000 and 2011. During this period, increases in explosive activity prior to effusive episodes were matched by rises in VRP values. Large radiant power values prior to effusion showed that the magma column was exposed at surface in Stromboli's crater. The feeding system had reached its capacity to contain the rising flux of magma. A similar mechanism is proposed for Fuego's paroxysms below.

What triggers a paroxysm at Volcán de Fuego? Petrographic analyses of eruptive products have informed several conceptual models for triggering paroxysmal eruptions. The earliest of these models presented a system fed by a discrete pair of magma chambers: a small, dike-like chamber at several kilometres' depth, and a deeper chamber of greater volume [Rose et al., 1978, Martin and Rose, 1981]. Later papers also cited the possibility of a third, larger chamber near the crust-mantle boundary [Chesner and Rose, 1984]. More recent literature invokes magma mixing across a range of depths rather than at discrete intervals [Berlo et al., 2012], with melt inclusions used to illustrate that material ejected in 1974 was sampled from a large range of depths prior to eruption (3 - 13 km) [Roggensack, 2001]. Berlo et al. [2012] used melt inclusions to investigate the link between different eruptive episodes at Fuego and concluded that the eruptive episodes of 1974 and 1999 onwards were driven by episodic injections of magma from a deeper source to the shallow subsurface, followed by the ascent of magma parcels to the surface. Deposits from 2017 pyroclastic flows subject to petrographic analysis include heterogeneous crystal textures similar to those observed in samples studied by Berlo et al. [2012], suggesting a common inception (Hannah Moore, pers. comm.). The model by Berlo et al. [2012] that conceives of Fuego's paroxysms being fed by pulses of magma would discourage comparison with the Stromboli model offered by Calvari et al. [2011], which assumes a steady magmatic supply rate. However, Berlo et al.'s paper precedes the 2015 - 2018 eruptive cycle and its remarkably consistent paroxysms.

Fuego's recent paroxysmal cycle may be explained by a consistent increase in magma influx from the lower feeding system into its upper conduit. Just as at Stromboli, where VRP increases seen in the days before effusive onset indicated that its conduit was at capacity, peaks in VRP values at Fuego seen during paroxysm indicate that its conduit is full. Persistent lava effusion and energetic explosions throughout paroxysm at Fuego suggest a continuous supply of magma. This journey may be traced from depth to surface, beginning with influx of fresh magma into Fuego's lower feeding system. This material rises to the base of Fuego's upper conduit. The magma already in the conduit is pushed up and its upper portion decompresses, driving an initial increase in explosions at summit. Although at Stromboli explosive activity generally precedes lava effusion [Calvari et al., 2011], lava flow formation at Fuego is associated with agglutination of material produced by fire fountaining (see next paragraph). This could explain how increases in explosions and lava flow effusion occur simultaneously. Returning to the model: if increased magma influx at depth persists, then non-degassed magma in Fuego's lower conduit may be forced upwards and decompress violently as volatiles are released. This would fuel a sustained eruptive plume that is observed during recent paroxysmal climaxes at Fuego. The climactic period would continue until the volume of magma in Fuego's conduit had been sufficiently depleted to exhaust decompression of rising magma. However, continued supply from base would soon drive the next paroxysm. The increase in magma supply rate to Fuego's deeper system would need to be both rapid and sustained to sustain a 3.5-year cycle of monthly paroxysms. A potentially fruitful avenue of future research could estimate volume of eruptive products for each paroxysm and consequently suggest magmatic processes that could deliver the required volume to Fuego's plumbing system at relevant timescales.

The model proposed above agrees with that proposed by Calvari et al. [2011] in Section 2.6.1. That model assumes relative stability in the geometry and volumetric capacity of Stromboli's conduit, magma composition, and supply rate over the period of study. Such assumptions are plausible at Fuego for the 2015 - 2018 paroxysmal cycle. Studies cited in the previous paragraph all present a relatively simple geometry, while the consistency of supply rate during this period may be proven by the timings of the paroxysms themselves, which occurred almost monthly (every 30 - 45 days). If accurate, this model generates further questions about the magmatic system supplying Fuego. What processes occurring at depth caused an increase in magmatic supply rate? And, given the change in activity since 2018 (see Section 2.6.4), what ended the increase? Recent work on glass compositions of Fuego and other mafic systems provide some clues, suggesting that high-intensity eruptions are related to magma sourced from a broad range of pressures

[Cashman and Edmonds, 2019]. This includes both deep-sourced magma ascending rapidly after decompression and magma stored temporarily in the shallow system by consistent mafic recharge. However, it is still unclear how closely Fuego's shallow storage and deep accumulation regions are connected, and to what degree the two regions confer outside of its paroxysms. Answers to these questions may lie in understanding of the complex tectonic interplay below Fuego, but are unfortunately beyond the scope of this chapter.

An alternative explanation that has not previously been considered for triggering paroxysm at Fuego is the gravity-driven shedding of material from an ephemeral summit cone. In this model, persistent lava fountaining accumulates ballistic material in the summit crater as an ephemeral cone. Lava flow effusion begins when the full summit crater overspills. When travelling on a high initial slope angle, flows may pass the glass transition and deteriorate to fractured avalanches, before reagglutinating at lower altitudes as the slope angle decreases [Sumner, 1998, Escobar Wolf, 2013]. If the flow output rate were sufficiently high, lava flow effusion could destroy the ephemeral cone and remove enough volume to depressurize the magmatic system, thus triggering a paroxysmal eruption. In several paroxysms since 2015 Fuego had a visible depression in its the summit crater (e.g., 3rd January 2016): therefore, this model cannot work as a general explanation for triggering paroxysm. However, it may be invoked in specific cases where an ephemeral cone was observed prior to paroxysm (e.g., the paroxysms of 25th February 2017 and 12th October 2018).

There are several factors to consider regarding the methods used to study the accelerating cycle of explosive paroxysms observed at Fuego since 2015. Several of the largest paroxysms of this period (for example: 5th May 2017, 3rd June 2018) were associated with relatively small VRP values. Both paroxysms generated eruptive columns >6,000 m asl and extensive pyroclastic flows, and the 5th May 2017 paroxysm produced extensive lava flows, yet neither was associated with a VRP value of >500 MW. A possible explanation may be attenuation of thermal anomalies tracked by MIROVA. The presence of meteorological clouds or volcanic plumes may cause partial or complete attenuation, as may the azimuth and zenith of the acquiring satellite relative to the source of thermal anomaly. These factors are difficult to quantify and must be evaluated on an image-by-image basis. Some of the bias caused by these factors may be removed by introducing a minimum threshold below which VRP values may be excluded, assuming they represent values taken under cloudy conditions or at extreme acquisition geometries [Coppola et al., 2012]. An alternative interpretation could be that these paroxysms did not generate large VRP values because the majority of the eruptive volume they produced was in the form of pyroclastic flow material. In this case, the fine-grained material composing much of these flows cools rapidly (within hours), and would not produce a strong radiative power signal detectable by MIROVA. If this were true, the resulting bias would unfortunately not be mitigated by introduction of a minimum inclusion threshold. Ultimately, the absolute value of any single VRP measurement may be affected by any of the factors mentioned above, and direct comparison between individual

VRP values may be biased. Nevertheless, there remains strong evidence for the association between VRP values >200 MW and thermal emission from hot surfaces including lava flows, incandescent fountaining, and Strombolian eruptions that represent above-background activity (including paroxysmal eruption) at Fuego.

2.6.3 Implications for eruptive hazards

Although the flanks of Volcán de Fuego were populated when the 1974 eruptive episode occurred, academic literature contains few references to the impacts of the episode on these populations. Nevertheless, the tephra and pyroclastic flow material generated likely had impacts similar to those caused by the large-magnitude eruptions in 1971 and 1973, elaborated on by Bonis and Salazar [1973]. In the decades since the 1974 eruption, the lands that surround Fuego have undergone considerable development. There are schools, residential communities, and industrial facilities near the volcano. RN-14, the highway that serves as the principal trade route between Mexico and Guatemala, crosses several rivers which drain the Fuego volcanic area and are primary lahar routes (see Figure 2.1). Many tens of thousands of people live near Fuego: >50,000 live within 10 km, and >1,000,000 within 30 km, of its summit [Venzke, 2013]. The majority of these people live in poverty, relying on agriculture for their livelihood [Graves, 2007, de Estadística Guatemala, 2013]. The various hazards associated with Fuego have previously been considered, both in USGS reports and in hazard maps produced by INSIVUMEH following the 3rd June 2018 eruption [Vallance et al., 2001, INSIVUMEH, 2018]. Implications of this chapter's results for understanding these hazards are discussed below.

The most severe and immediate hazard of Volcán de Fuego, in the case of a large-magnitude explosive paroxysm, is pyroclastic flows; and the regions most obviously vulnerable to pyroclastic flow hazard are those located close to Fuego's barrancas. Communities such as Sangre de Cristo (located at OVFGO2 in Figure 2.1) have been evacuated multiple times since 2015 because of risk deriving from paroxysm-generated pyroclastic flows. More recently and devastatingly, pyroclastic flows generated by the 3rd June 2018 eruption travelled >12 km down Barranca Las Lajas and destroyed both the Las Lajas bridge and the community of San Miguel Los Lotes, killing several hundred people (for locations, see Figure 2.1). Preliminary estimates put the pyroclastic flow deposit volume in Barranca Las Lajas somewhere between 20 and 30 million m^3. This figure is comparable to volume estimates for pyroclastic flows produced by explosive paroxysms between 1999 and 2018: for instance, the 21st May 1999 eruption produced 0.0255 km^3 of pyroclastic flow material, and the 13th September 2012 eruption produced 0.0269 km^3 [Escobar Wolf, 2013]. However, the greater frequency of paroxysms and paroxysm-generated pyroclastic flows since 2015 has important hazard implications because of the more frequent exposure of nearby communities to risk deriving from those hazards. Furthermore, paroxysms occurring since 2015 illustrate two points regarding risk generated from pyroclastic flows of Fuego: first, that during a paroxysm, pyroclastic flows are typically generated in multiple barrancas, thus simultaneously increasing risk in multiple areas; second, that pyroclastic flows may be a major hazard to communities beyond those closest to barrancas. San Miguel Los Lotes was not considered to be especially at risk of pyroclastic flow, but the sequential descent of multiple flows down Barranca Las Lajas may have filled the barranca and caused overspill further down Fuego's flanks. The increase of paroxysms since 2015 has important pyroclastic flow hazard implications both at the moment of descent and subsequently, due to the greater accumulation of material.

Airborne ash and ash fall from eruptions of Volcán de Fuego have persistently affected both local and distant populations in Guatemala. Due to the hazard airborne ash presents to planes, air traffic corridor R644, which runs close to the volcano and was primarily used for traffic to Mexico, is now permanently closed, resulting in rerouting of flights (Ivan Velasquez, pers. comm.). This is a direct result of the increase in explosive paroxysms since 2015. Eruptions smaller than those of 1974 have produced tephra that has had significant impact; the eruption of 13th September 2012 forced the closure of La Aurora International Airport in Guatemala City for three days, costing the country millions of dollars in revenue. An increase in paroxysmal frequency could have similar or greater economic impact. Meanwhile, tephra fallout will be the principal far-reaching hazard of a future paroxysm, potentially severely impacting Guatemala City (40 km E of Fuego), or Quetzaltenango (80 km NW), i.e., one of the two largest Guatemalan cities. Closer to Fuego, the negative impact of regular ash fall caused by frequent paroxysms on crop productivity is unstudied but potentially significant.

An intense annual rainy season in Guatemala, combined with the large volume of pyroclastic material deposited on Fuego's flanks, ensure that lahars from the volcano are frequent and powerful. Lahars may reach extraordinary dimensions of over 40 m width and 4 m depth and speeds greater than 8 m/s [Schilling et al., 2001, Escobar Wolf, 2013]. Lahars generated since 2015 can be exceptionally long-ranging: in August 2017 they destroyed a Scout encampment (known as "Finca Scout", located 14.34°N, 90.95°W; see FS on Figure 2.1) and a bridge that borders the Ceniza river 20 km downstream of Fuego. The massive volume of pyroclastic material deposited since 2015 will supply future large lahars, with both direct hazards and resulting hazards associated with sediment transport in the rivers draining Fuego. Lahars from Fuego do not only occur during eruption, and associated risks are always present.

If the current magmatic conditions at Fuego persist, one would expect that the frequent paroxysmal eruptions seen in 2015 – 2018 would continue throughout 2018 and beyond. Indeed, paroxysmal eruptions occurring on 12th October and 18th November suggest this is the case. However, the eruption of June 3rd, 2018 was of a different character from other paroxysms in this period: preceded by a greater period of quiescence, and possibly not preceded by lava effusion[3]. Therefore, it is possible that the frequent paroxysms that have characterized Fuego's

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[3] As mentioned in 2.6.2, the presence of meteorological cloud is a possible explanation for attenuation of VRP signal. Both ground-based observations and satellite detection agree on the presence of cloud throughout much of the 3rd June 2018 eruption.

recent activity will not continue. Alternatively, the 3rd June eruption could herald another period of extraordinarily high activity, just as activity in the early 1970s included large eruptions in 1971 and 1973 and a cluster of sub-Plinian eruptive activity in 1974. Lyons et al. [2010] did note the increase in paroxysmal frequency during their period of observation (2005 – 2007) and suggest that the observed increase in explosive activity could suggest a transition to less open-vent conditions, with significant hazard implications. In that case the increase preceded a 5-year hiatus in paroxysms. Of course, past behaviour is not necessarily an indicator of future activity. However, the increase in paroxysmal frequency since 2015 re-emphasises this concern and underscores the need for continued study of Fuego's paroxysmal eruptions as a critical factor in future risk mitigation efforts.

2.6.4 Recent activity of Fuego

The work presented in this chapter was concluded in 2019. In the two years since, Fuego's eruptive behaviour has changed considerably. This informs discussions of models for triggering paroxysm and of hazards presented in Sections 2.6.2 and 2.6.3.

Fuego produced a paroxysmal eruption on 18th November 2018. This eruption was preceded by lava effusion and culminated in pyroclastic flows, similar to other paroxysms in the 2015 - 2018 cycle. This paroxysm appears to be the last in the cycle. In 2019, Fuego's activity was characterized by small ash explosions from summit and occasional avalanches [Venzke, 2013]. There were intermittent episodes of incandescent fire fountaining reaching 200 - 400 m above summit, and individual short lava flows (500 - 800m) were recorded in March - May and November 2019 in the Barranca Seca drainage (adjacent to Barranca Santa Teresa). Fuego did not produce pyroclastic flows or simultaneous lava flows in multiple ravines in 2019 [Venzke, 2013]. Fuego's activity increased in 2020 with effusion of lava flows in southern drainage ravines (Barrancas Ceniza and Trinidad) in late March (see Figure 2.10). The volcano continued to produce ash explosions from summit. Effusive activity continued between April and June with several episodes of parallel lava flow production in Barrancas Ceniza and Seca [Venzke, 2013]. Many lava flow fronts produced block avalanches that descended Fuego's ravines. Activity in August - November 2020 was similar to the first half of the year, with INSIVUMEH reporting 6 - 12 explosions per hour from Fuego's summit, occasional lava flow effusion, and block avalanches descending multiple barrancas. In 2021 activity continues at a low level. INSIVUMEH reported 5 - 11 explosions per hour from Fuego's summit generating shock waves felt in local communities and ash plumes reaching 1 km above the crater. Ejection of incandescent material was recorded almost daily, reaching up to 300 m above the summit [Venzke, 2013].

In this thesis, the model most clearly explored to explain Fuego's 2015 - 2018 paroxysmal cycle invoked a sustained increase in magma influx to the lower feeding system into its upper conduit (see Section 2.6.2). The extraordinarily large paroxysm of 3rd June 2018 provoked the

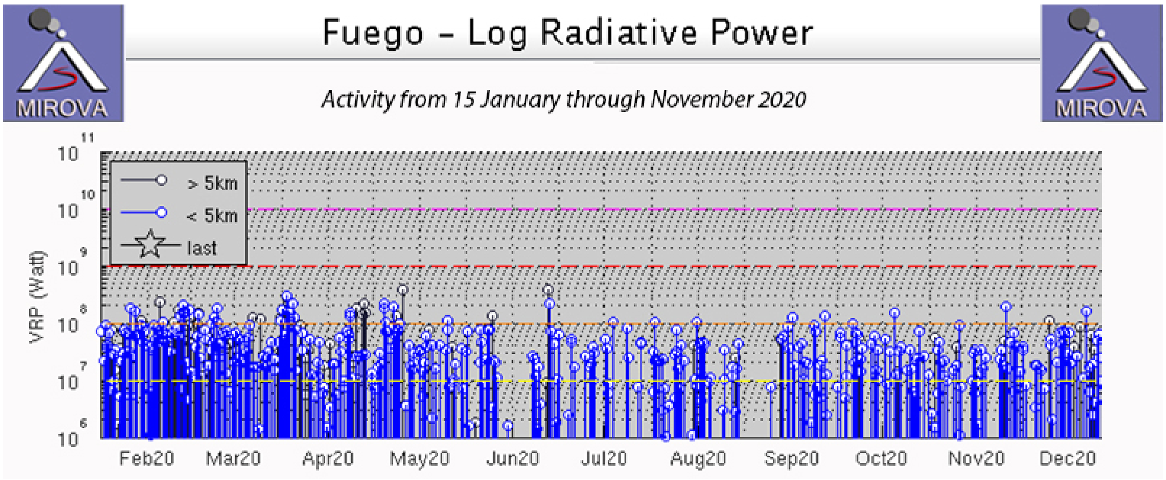

FIGURE 2.10. Plot of Fuego's activity from 15th January to November 2020 illustrated by VRP values from the MIROVA database. VRP values consistently range between 10 and 100 MW for the year, indicating 'moderate to high heat flow'. From `www.mirovaweb.it`.

question of what eruptive behaviour would follow: whether this paroxysm would open a period of elevated activity similar to the 1970s, or whether activity would decline to pre-2015 levels 2.6.3. It is possible that Fuego may imminently produce a large (VEI 3+) eruption. However, in the 2.5 years since Fuego's November 2018 paroxysm, the volcano has entered a period of lower activity similar to 2008 - 2011. This period was characterized by occasional fire fountaining and lava effusion, and an absence of explosive eruptions with a large eruptive plume. The most simple explanation for Fuego's decline in eruptive energy since November 2018 is the decrease of magmatic supply at depth. However, previous studies have observed development in Fuego's magmas towards a more evolved chemistry [Berlo et al., 2012]. Confirmation that Fuego is not moving towards a closed system (potentially associated with an increase in hazard) could be confirmed by continued petrological analyses of recent eruptive products of the volcano.

Section 2.6.3 discussed the immediacy and reach of hazards associated with eruptions of Fuego. Since the November 2018 paroxysm, Fuego has not produced pyroclastic flows that have provoked evacuation. This is positive given the logistical difficulties and threat to livelihoods that evacuation represents to many local residents (see Chapter 3 for more detail). However, as stated by the official quoted in 3.7.2.3, this temporary reprieve in pyroclastic flow hazard is an opportunity for CONRED to strengthen their communication network and provide the resources that locals need to enact self-evacuation in the event of a future large eruption of Fuego.

Strengthening of CONRED's communication network should ideally be paralleled by reinforcing INSIVUMEH's monitoring network, so that information shared within the network can be both more detailed and more frequent. INSIVUMEH's monitoring capacity has increased greatly since 3_{rd} June 2018. Then, monitoring comprised visual observations from OVFGO1 combined with RSAM measurements from two seismometers (FG8 and FG3), the latter of which was not functioning during the eruption [Alvarez, 2019]. In 2021, INSIVUMEH have a permanent seismo-acoustic network comprising three seismo-acoustic arrays, three broadband seismic stations, and a 6-channel infrasound array [Díaz Moreno et al., 2020]. Data from this network are supplemented by regular satellite observations including radiance measurements from NASA's GOES-16 satellite. Analysis of infrasound signals has recently provided the first characterization of various activities and hazards of Fuego in this medium, including of lahars [Díaz Moreno et al., 2020].

The 15.1 million m^3 of pyroclastic flow deposits produced on 3rd June 2018 [Albino et al., 2020] will be the source material for many powerful lahars. The most powerful to date occurred on 9th October 2020, when heavy rains produced lahars in all of Fuego's barrancas [INSIVUMEH, 2020]. Areas near Barranca Las Lajas previously deemed "high-risk" were most immediately affected, including highway RN-14 that was devastated in June 2018 (Figure 2.11). Unfortunately, this overflow is at least partly caused by human efforts. In a bulletin released on 9th October 2020, INSIVUMEH reported that the problem was "caused by the poor management of dams and of material accumulated by diggers ... the strong rains of recent days broke the dams and moved material accumulated by this company in the form of a current of volcanic material over RN-14" [INSIVUMEH, 2020]. The bulletin cautions that this issue is likely to reoccur at Fuego, and indeed the remobilization of pyroclastic flow material as lahars has damaged or destroyed several bridges around Fuego since 1999. Areas in which lahar hazard may be mitigated include judicious land-use planning, engineered protection structures, and lahar early warning systems (EWS) [Pierson et al., 2014]. Some progress on EWS has been made on the latter with the installation of a seismic network around Fuego since June 2018 (Amilcar Roca, pers. comm.). Challenge to progress in the other areas can be partly attributed to a lack of formal communication between INSIVUMEH and the companies responsible for building dams from pyroclastic flow deposits in Fuego's barrancas. Potential progress could be made by building such communication so INSIVUMEH's scientists can assume an advisory role and work together with other stakeholders, as suggested by Pierson et al. [2014].

FIGURE 2.11. Photograph of lahars crossing RN-14 on 9th October 2020 produced by mobilisation of 3rd June 2018 pyroclastic flow deposits in Barranca Las Lajas. From INSIVUMEH [2020].

2.7 Conclusions

Volcán de Fuego's frequent activity and geographical situation renders it an ideal subject for synchronous study of eruptive activity and volcanic hazard. The sub-Plinian eruptive episode of October 1974 has allowed analyses of the subsurface magmatic system of Fuego, while eruptions between 1971 and 1974 have highlighted the possibility of multiple large-magnitude eruptions occurring in sequential years at Fuego.

A new eruptive regime beginning in January 2015 and characterized by regular paroxysmal eruptions consistently preceded by lava effusion can be traced in satellite remote sensing data and corroborated by seismic and visual observations. Tracing the details of the new eruptive regime allows for consideration of various models to explain the triggering cause for paroxysm. While further study is required to elucidate trigger(s) of paroxysm at Fuego, there may be merit in considering recent models based on behaviour of Stromboli, where paroxysm is triggered by decompression of the shallow conduit by lava effusion. We propose that the MIROVA database is an effective tool for comprehending long-term changes in eruptive activity at Volcán de Fuego, and may significantly improve volcano monitoring capacity at Fuego, and possibly at other open-vent systems.

The eruption of 3rd June 2018 killed hundreds of people in San Miguel Los Lotes and destroyed La Reunión resort, and tragically showed the potential of these paroxysmal eruptions to cause great damage. INSIVUMEH and CONRED are acting with the international volcanological community and local communities to prepare for another such paroxysm, by increasing hazard monitoring and forecasting for Fuego, and producing a series of hazard assessments. Mitigation of risks associated with persistent activity of Fuego will require continued co-operation between these groups.

CHAPTER 3

FIRESIDE TALES

> Maybe stories are just data with a soul.
>
> *Brené Brown*

*This chapter has previously been published as: '**Fireside Tales: understanding experiences of previous eruptions and factors that influence the decision to evacuate from volcanic activity of Fuego"** in VOLCANICA. The published manuscript was co-authored with Dr. Teresa Armijos (UEA), Edgar Antonio Barrios Escobar (INSIVUMEH), William Chigna (CONRED), and Professor. I. Matthew Watson (University of Bristol). I designed the study, led fieldwork, analysed transcripts, translated interview data, and led drafting of the manuscript. TA guided the study design throughout fieldwork and contributed to the development of the manuscript. EB and WC assisted in data collection. IMW assisted with fieldwork and contributed to writing. All authors made a substantial and intellectual contribution to the work and approved it for publication.*

3.1 Abstract

Fuego is capable of catastrophic eruptions like that of 3rd June 2018, which triggered pyroclastic flows that devastated the community of San Miguel Los Lotes and caused hundreds of fatalities and severe long-term socio-economic impacts. Future volcanic risk mitigation efforts are likely to involve temporary evacuation of local communities, the success of which requires co-operation between locals, scientists, and decision-makers. However, locals' experiences of eruptive activity, and how these experiences influence their responses to

evacuation, have not been studied in detail. In 2019 I conducted an investigation of these themes through qualitative research methods involving semi-structured interviews that focussed on direct experience as opposed to volcanic risk perception. I found significant differences between scientists' and locals' observations of Fuego's activity. Furthermore, a clear disparity emerged between communities on Fuego's west and east flanks in terms of direct prior experience of eruptions and communication with INSIVUMEH/CONRED. These findings have significant implications for future evacuation efforts at Fuego and at analogous volcanoes.

3.2 Introduction

On 3rd June 2018, a paroxysmal eruption of Fuego generated a series of pyroclastic flows that descended Barranca Las Lajas and buried the community of San Miguel Los Lotes. 332 people have been reported as officially missing, although independent estimates suggest that up to 2,900 people were killed [News, 2018a]. In addition, an estimated 5,000 people lost their homes and had to resettle elsewhere [News, 2018b]. In Guatemala the mandate for monitoring volcanic unrest and issuing alert information lies with INSIVUMEH, while CONRED is responsible for co-ordinating disaster response and community preparedness for natural hazards. On 3rd June, INSIVUMEH released bulletin reports of activity continuously from 06:30 a.m., and CONRED staff attended both the Las Lajas bridge and Los Lotes in efforts to remove people from these high-risk areas. However, after the eruption, national media highlighted the disconnect between these authorities supposedly fulfilling their responsibilities regarding volcanic crisis and the high death toll. In particular, media focussed on the different fates of geographically close communities: why did the private golf resort of La Reunión successfully evacuate, yet Los Lotes, two kilometres further south, suffer such extensive human loss? [Tobar, 2018b]. This question relates to the larger issue of the ability and willingness of communities to evacuate from eruptive crisis. By investigating the different ways in which people experience Fuego's eruptive activity, and the factors that influence evacuation, this chapter provides some possible explanations and future actions to prevent these situations from happening again. It highlights the importance of understanding local residents' priorities, interests and decision-making processes when managing volcanic risk.

Pyroclastic flows are frequently produced by eruptive activity of Volcán de Fuego [Naismith et al., 2019a]. However, the estimated 15.1 million m^3 of pyroclastic flow material that was deposited in Las Lajas on 3rd June [Albino et al., 2020] was exceptionally large for eruptions of Fuego. It was more than double the average volume of pyroclastic flows registered since 1999 [Ferres and Escobar, 2018]. Nevertheless, eruptions producing smaller pyroclastic flow volumes have repeatedly triggered evacuation (e.g., September 2012, May 2017, November 2018). The high velocity and mobility of pyroclastic flows means that evacuation is the only procedure that effectively decreases exposure and prevents associated loss of life. However, evacuation is a complex and costly procedure that often involves significant management and resources from national authorities. Furthermore, longstanding social and economic pressures affecting members of communities such as Los Lotes mean they face additional challenges to comply with evacuation orders. Local residents may not interpret eruptive behaviour in the same ways as authorities do. Yet, as this chapter shows, authorities believe that locals have the capacity and responsibility to recognize changes in volcanic activity and to decide to evacuate themselves when volcanic risk increases. These differences in opinion, and the lack of agreed thresholds of volcanic risk above which protective action must occur, continue to generate risk for the people living near Volcán de Fuego. This chapter argues that understanding differences in direct lived experience of previous eruptions and in volcanic risk tolerance between locals and authorities is critical to effective volcanic risk mitigation (including evacuation). It does so through an exploration of memories of past eruptions and of the factors that influence peoples' decision-making in the face of volcanic crisis.

This chapter presents findings from studies conducted at Fuego in 2018 and 2019 that explicitly compare (1) how local people experience the activity of Fuego; (2) how members of INSIVUMEH and CONRED experience the activity of Fuego; (3) the potential implications of these differences for the success of current risk mitigation policy at Fuego. These findings show that although experiences of INSIVUMEH and CONRED staff of Fuego's recent paroxysmal activity are similar to the eruptive behavioural changes described in Chapter 2, local experiences of the same period are entirely different. Local people are highly aware of Fuego's activity and knowledgeable of most volcanic hazards; however, since Fuego's reactivation in 1999, the only eruptions they clearly remember and identify are those that required a community-wide response which interrupted day-to-day life (e.g., May 2017, June and November 2018). Both local residents and authorities remember the events that matter to them, showing that what matters to them is different.

Local people experience the effects of persistent eruptive activity as they impact on day-to-day life. The root causes of risk identified in many volcanically active environments are present at Fuego. However, an additional component of volcanic risk apparent at Fuego is the disparity between communities on its west and east flanks in terms of experience of previous activity and communication with INSIVUMEH and CONRED. Through reference to volcanic risk perception and evacuation literature, this chapter confirms that direct experience of eruptions is only one of many factors informing response to eruptive crisis at Fuego. For local residents many competing factors (including existing socio-economic pressures and specific impacts associated with evacuation) create conditions that make it much more difficult to evacuate. At Fuego, CONRED's current evacuation policy places the majority of the responsibility for evacuation on locals, ignoring the implications of these competing factors. Both the great variability in experiences of eruptive activity (both between INSIVUMEH/CONRED and locals, and between locals in different communities) and the social pressures affecting locals have implications for volcanic risk and preparedness at Fuego. These act in opposition to any potential increase in local risk awareness and may have severe consequences for the success of future evacuations.

3.3 Exposition: Communication between stakeholder groups at Fuego

Volcanic risk mitigation at Fuego is managed through a network of institutions and communities of residents around the volcano. Table 3.1 defines acronyms of several institutions in this network. Figure 3.2 shows how these institutions communicate between themselves and with the public. INSIVUMEH was founded in March 1976 after the 4th February 1976 Guatemala earthquake. The institution is responsible for monitoring geophysical phenomena and advising the government and private sector on natural hazards. INSIVUMEH monitor volcanic activity through a geophysical monitoring network managed from a central office in Guatemala City, aided by visual observations of observers located in two observatories in the communities of Panimaché Uno (OVFGO1) and Sangre de Cristo (OVFGO2)[1]. These observers have been appointed by INSIVUMEH from residents of those communities. CONRED was founded in 1996 to reduce the impacts of disasters on Guatemalan society and to co-ordinate relief efforts. CONRED is a tiered organization with sub-organizations on the regional (CORRED), departmental (CODRED), municipal (COMRED), and local (COLRED) scale. The central office of CONRED, SE-CONRED, is located in Guatemala City. At Volcán de Fuego, CONRED carries out training in hazard awareness and preparatory actions among local communities. This is achieved primarily through a subsidiary office, Unidad de Prevención en Volcanes - *(Volcano Prevention Unit)* (UPV) in Antigua Guatemala which organizes voluntary community groups known as COLREDes in local communities. UPV communicates with these communities via in-person visits, radio, and WhatsApp. Radio UPV is the network of community radio bases. As of April 2019, UPV has radio bases installed in 28 communities and two private farms (fincas) around Fuego. Each community radio base is located in the home of a radio operator who also belongs to that community's COLRED. Participation of COLRED members is highly variable due to difficulties in good telephone signal and prohibitive costs of mobile data preventing local peoples' access to the conversation.

CONRED has an alert level system for the communication of risk from natural hazards including volcanic eruptions. This system comprises four colours or alert levels with associated recommendations for action. The levels are: green or "Vigilance" (continue with normal activity); yellow or "Prevention" (prepare to act and follow authorities' instructions) amber or "Danger" (keep alert, prepare to evacuate if necessary in case of any sign of danger); and red "Emergency" (evacuate danger zones, remain in provisional shelters; follow authorities' instructions) (Figure 3.1).

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[1] After the events of 3rd June 2018, Sangre de Cristo was evacuated and its observer relocated to Panimaché Uno. By the end of my fieldwork in April 2019, this observer was still in Panimaché Uno and working at OVFGO1.

FIGURE 3.1. CONRED alert level system for various natural hazards with associated recommendations for action. Retrieved from `https://aprende.guatemala.com/cultura-guatemalteca/actualidad/significado-alertas-conred-guatemala/`. Last accessed 07/02/2021.

In Guatemala, institutional policy defines the recommended course of action required to protect lives of local residents during eruptive crisis. As of January 2021, CONRED maintain a policy of *auto-evacuación* (self-evacuation) at Volcán de Fuego. This policy requires active involvement of a community in decision and responsive action. Evacuation is deemed necessary when CONRED issue a red "Emergency" alert level for eruptive activity of Fuego. The decision to evacuate a community from activity of Fuego should be made in agreement between a community's COLRED and its local council or Consejos Comunitarios de Desarrollo - *(Community Development Council)* (COCODE). Furthermore, in the self-evacuation policy, a community is supposed to manage the initial stages of evacuation including gathering family members, moving to a pre-defined safe point, and beginning to leave a community on foot or by vehicle if necessary. Communication would ideally be maintained with UPV throughout evacuation. Theoretically, a community which initiates its own evacuation would find a secondary response co-ordinated by UPV involving temporary evacuation shelters and transport from the safe point to the shelters. In reality, several factors prevent this policy from working as it should; these factors are explored in Section 3.6. A full description of the roles of CONRED and INSIVUMEH can be found in the National Response Plan on CONRED's website (`https://www.conred.gob.gt/site/Plan-Nacional-de-Respuesta`).

INSIVUMEH release information on Fuego's activity through bulletin reports that are published on their website (`www.insivumeh.gob.gt`) and on Twitter. Bulletin reports first travel to a central radio operator called ALFA before being delivered to other organizations, including CONRED. Published reports are further disseminated through Radio UPV and on WhatsApp. Figure 3.2 shows formal pathways of communication between institutions and the public regarding eruptive activity of Fuego. This diagram was created for this thesis with colleagues in INSIVUMEH and CONRED, as such a diagram does not exist in either institution's documentation. This figure does not include informal communication pathways around the volcano: for instance, the volcanologists of INSIVUMEH frequently communicate directly with UPV via phone and instant messaging during eruptive crisis. While in theory the roles of INSIVUMEH and CONRED are distinct, there is no single piece of documentation that clearly separates their responsibilities, and in practice the institutions' efforts frequently overlap. This confusion has implications for personal and institutional responsibility for volcanic risk mitigation at Fuego.

Acronyms	
ALFA	INSIVUMEH's comms centre for information dissemination
CTE	CONRED's centre of transmissions for emergencies
COCODE	Community Development Council
COLRED	Local Co-ordinator for Disaster Reduction
DGAC	Civil Aviation Authority
OVFGO1	Observatory One of Volcán de Fuego
OVFGO1	Observatory Two of Volcán de Fuego
INSIVUMEH	National Institute of Seismology, Volcanology, Meteorology, and Hydrology
SE-CONRED	Executive Secretary of CONRED
UPV	Volcano Prevention Unit
RADIO UPV	Network of community radio bases managed by UPV

Table 3.1: List of acronyms for various institutions and groups involved in volcanic risk mitigation at Volcán de Fuego. Communication between the institutions is shown in Figure 3.2.

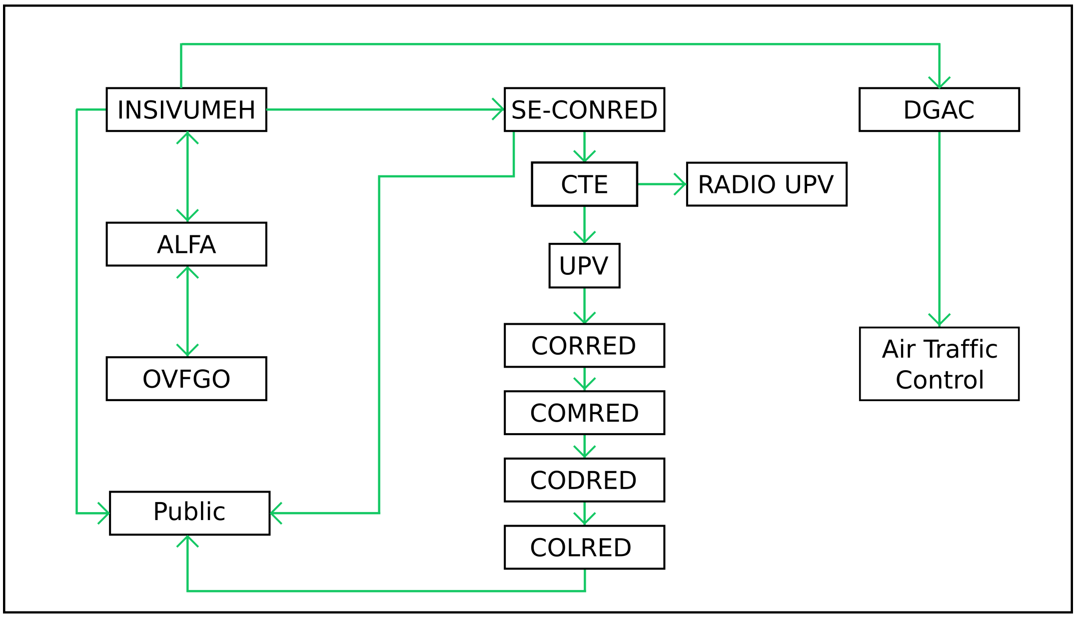

FIGURE 3.2. Schematic of different institutions and communities affected by activity of Volcán de Fuego showing formal pathways of communication between them. Diagram co-created with G. Chigna and W. Chigna.

3.4 Theoretical framework

3.4.1 Root causes of volcanic risk

3.4.1.1 Developments in risk paradigms

Advances in volcanic risk research are associated with an increasing recognition of the uniqueness of both volcanic systems and surrounding communities. Such uniqueness makes volcanic risk more complex.[2] Gaillard [2008] provides an excellent synopsis that outlines alternative paradigms within the evolving discipline. He identifies the work of White [1945] as pioneering in centralizing risk within the study of natural hazards; White argued that human response to natural hazard is formed of a combination of adjustment to one's environment and implementing practices to minimize loss. Later supporters of this approach (the 'hazard-adjustment' approach) argued that hazard response was ruled by individual choice – whether unconscious or deliberate ([Burton, 1993]).

In the 1970s a second paradigm emerged to counter the dominant hazard-adjustment approach. Supporters of the new paradigm were concerned that natural hazard researchers were fixated on extreme natural events as the driving force of disasters at the cost of overlooking root social causes of risk: "the initiative in calamity is seen to be with nature, which decides where

---

[2] See Bonis and Salazar [1973]: "But, every volcano, like a woman, has its individual temperament and cannot be taken for granted."

and what conditions or responses will become significant.” [Hewitt, 1983]. In response to these criticisms of the hazard-adjustment approach, the new paradigm of ’vulnerability’ focussed on existing socio-economic conditions in an individual’s environment that produce disaster. This paradigm was developed by research in areas where daily life was difficult to distinguish from disaster [Blaikie et al., 2005], and promoted pre-existing socio-economic factors to the primary cause of risk. Comprehending these factors was increasingly seen as the key to understanding how disasters develop. This constituted a major advance in risk research that did not disregard the importance of the natural hazard in producing disaster but rather relegated it to a dependent position, contingent on existing social factors:

> Being at risk of disaster is shown to be the chance that the characteristics of people generated by these political-economic conditions coincide in time and space with an extreme ‘trigger event’ natural hazard to which they have been made vulnerable.

Blaikie et al. [2005]

In the late 1990s, preservation of livelihoods was identified as a key feature of vulnerability that put an individual at risk. Both in more economically developed countries ([Dibben, 2008]) and less ([Lane et al., 2003]), livelihoods were acknowledged as an essential element of vulnerability that both prevented people from leaving a high-risk zone and encouraged their return before risk had decreased. At Volcán Tungurahua in Ecuador, efforts to create livelihood alternatives outside areas of high volcanic risk have evolved with adaptive forms of risk management. Here, local residents benefit from the greater security of such alternative livelihoods and take collective decisions to temporarily evacuate, thus minimizing the disruptive effects of forced evacuation [Armijos and Few, 2015]. Community engagement with temporary evacuation has been observed in volcanic environments as different as Tungurahua and Mt. Merapi, Indonesia [Andreastuti et al., 2019].

Researchers have latterly tried to unite the alternative risk paradigms of hazard-adjustment and vulnerability. Many argue that neither is alone sufficient to answer questions of risk mitigation, and both are required to make useful recommendations to policy-makers [Chester et al., 1999]. This has sparked an explosion in interdisciplinary research, where physical and social scientists unite to deliver multi-faceted approaches to volcanic risk (e.g., Armijos et al. [2017]).

Although academics are increasingly pursuing an interdisciplinary approach to consider together social and physical drivers of volcanic risk, there is evidence that these drivers are not of equal priority in local peoples’ response to volcanic activity. Local people respond to socio-economic pressures before adjusting to hazard, both in economically developing countries (e.g., Gaillard, 2008) and in countries which are relatively wealthy (e.g., Dibben, 2008). In environments where increased awareness of risk should (according to scientific consensus) require increased preparedness, locals consistently appear to underestimate volcanic risk [Donovan et al., 2014]. An apparent underestimation of risk has been observed in communities near Katla, Iceland [Jóhannesdóttir and Gísladóttir, 2010] and Mt. Ruapehu, New Zealand [Johnston et al., 1999]. There is a lot of literature on volcanic risk that presents local residents' perspectives of volcanic risk. This chapter contributes to the relatively small body of volcanological literature that simultaneously presents perspectives of multiple stakeholder groups (local residents, volcanologists, and officials) in a single volcanic environment.

The view that locals underestimate volcanic risk can lead to the mistaken belief that local people are deficient in knowledge or have miscalculated their priorities. In fact, communities affected by natural hazards often develop cultures of coping to adapt to their environment [Bankoff, 2004]. Conversely, academic knowledge of risk is not authoritative, although this group is often credited with an 'accurate perception' of the risk [Christie et al., 2015]. This is illustrated by a recent review of perception and social behaviour associated with various natural hazards including floods, earthquakes, and volcanic eruptions [Wachinger et al., 2013]. The review found no consistent influence of multiple personal factors (including age, gender, or level of education) on individual risk perception, despite widespread academic belief that these factors are influential [Wachinger et al., 2013]. The only definitive drivers of volcanic risk were (1) communication and trust between locals and authorities, and (2) direct previous experience of hazard. The second indicator is tempered by the degree of severity involved in the experience:

> "If in the past the event did not hit me negatively, I will escape also negative consequences of future events." This shows that it is less the experience "in itself", but rather the severity of the personal consequences experienced in past events that shapes the respondents' perceptions.
>
> Wachinger et al. [2013]

This review concluded that both the quality of direct experience of hazard and of relationships with authorities is critical in determining the circumstances of risk in a hazardous environment (e.g., at an active volcano). Furthermore, these drivers are themselves volatile: as volcanic eruptions rarely develop consistently, they will variably affect surrounding populations. Thus risk will vary even between neighbouring communities around the same volcano [Donovan et al., 2012a].

3.4.1.2 Different points of view

Local knowledge has the advantage of coming from direct experience of activity [van Manen, 2014]. Recent research shows the importance of including local peoples' experiences in managing volcanic risk, including in decision-making during crisis. Recognition of the flaws in a traditional linear approach to communicating risk [Donovan and Oppenheimer, 2014, Donovan et al., 2014]; successful integration of local and academic knowledge for participatory risk mitigation [Cronin et al., 2004]; and evidence that locals have a clear understanding of how volcanic hazards may affect their lives [Gaillard, 2008] have all highlighted the valuable contributions that local knowledge can make to understanding volcanic risk. Conversely, a failure to integrate local and institutional knowledge in volcanic risk management often proves ineffective in reducing risk to the most vulnerable [Gaillard and Mercer, 2013].

Storytelling is an aspect of local knowledge that may be particularly important for volcanic risk mitigation. Many disparate populations have used oral tradition to comprehend the trauma of a volcanic eruption [Cashman and Cronin, 2008]. Although telling stories to understand volcanic eruption occurs in both preliterate and literate societies, this method has largely been neglected in modern volcanic hazard mitigation strategies [Cronin and Cashman, 2016]. Fortunately, this is changing. There is increasing recognition of the power of storytelling for building resilience to natural hazards in the Global South [Loon et al., 2020]. Storytelling as a tool for future disaster prevention is recognized in research disciplines other than natural hazards, such as technical safety [Hayes, 2018]. In this latter discipline, authors recognize that the responsibility for incorporating storytelling for effective disaster management lies with professional safety managers [Hayes, 2018]. This chapter draws its results from stories told by local residents around Volcán de Fuego to illustrate how storytelling may contain powerful truths about volcanic risk mitigation.

An emerging area within volcanic risk research is how different stakeholder groups focus attention on different periods of activity. Dove [2008] explored local and government perspectives of activity of Merapi volcano to argue that not only ‘risk perception’ but also the concept of risk itself varied: arguing that locals perceived less risk from the volcano than authorities "does not do justice to the fundamental differences in the ways the two parties perceive the volcano" [Dove, 2008]. At Merapi, locals contextualized changes in volcanic behaviour within their focus on long periods of calm, while authorities, by focussing on Merapi in times of crisis, ‘exoticized’ the volcano and separated it from daily life. While it is uncontroversial to state that a volcano demands more attention from authorities and scientists during an eruption, this difference in focus between stakeholders and consequent implications for volcanic risk and its mitigation has been little explored in other cultures and countries.

In contrast to the majority of complementary literature, this chapter explicitly studies “direct experience (of previous eruptive activity)” as opposed to “volcanic risk perception”. This decision was driven by my and my supervisors’ belief that focussing on the latter isolates volcanic risk as the only risk people face in a volcanically active environment. Instead, “volcanic risk perception ... is one form of risk perception balanced with other forms of perception including risks to livelihood and cultural heritage” [Gaillard, 2008]. I hope that by focussing on how different people experience eruptions, this chapter can contribute towards more complete answers to understand responses to volcanic activity of Fuego.

3.4.2 Factors affecting evacuation

The most effective action to reduce and mitigate risk to life relating to most volcanic hazards is evacuation. This decision is often difficult to make because all choices may have negative consequences. During an eruption, an individual may decide to reduce risk of personal damage when the eruption is at its climax. This decision. may involve evacuation, particularly if the hazards associated with the eruption are impossible to manage from that individual's current situation. But what factors influence the decision to evacuate, and which are inconsequential? Recent literature suggests that risk awareness is not a primary factor. While direct experience of a hazard may promote risk perception, it does not necessarily lead to better preparedness [Johnston et al., 1999]. Wachinger et al. [2013] attribute this weak link between an awareness of risk and preparedness action to three potential causes: first, experience and motivation (e.g., an individual understands the risk but perceives that benefits outweigh risk); second, trust and responsibility (e.g., an individual understands the risk but transfers responsibility elsewhere); third, personal ability (e.g., an individual understands the risk but does not have resources to affect the situation). Often the three causes can intersect. For example, at Montserrat, peoples' return to the exclusion zone despite persistent risk was driven by factors varying from economic hardship to a lack of shared thresholds of tolerable risk [Barclay et al., 2008]. To outsiders, this behaviour may appear illogical, occurring in the face of increased danger to life. Before making such a judgement, they should seek first to understand temporal and spatial changes in social, political, and economic factors, as well as changes in volcanic hazard and responses to risk, all of which may encourage return [Few et al., 2017]. Responses to risk are related to local priorities, which themselves are often closely linked to the existing social and economic pressures that place individuals at risk. Pressures that encourage evacuees to return while risk is still high can be summarized as "push" (e.g., poor shelter conditions) or "pull" (e.g., concern for livestock) factors (see Figure 3.3 [Barclay et al., 2019]). These pressures, as they express a desire to act against further impoverishment, may interfere with an otherwise apparently more logical desire to protect life.

Local actions labelled as "illogical" may instead be driven by misunderstandings arising from poor communication between stakeholder groups that lead to disagreement regarding the nature of the risk and a disincentive to evacuate (e.g., in the reoccupation in the town of Baños near Volcán Tungurahua described by Lane et al. [2003]). In addition to breakdowns in communication, difficulties in evacuation management may occur because of peoples' resistance to leaving an area of high risk [Mei et al., 2013], driven by factors such as place attachment and security fears. Mei et al. [2013] identified five interrelated factors negatively affecting successful evacuation, including uncertainty in forecasting eruption and resistance associated with economic factors.

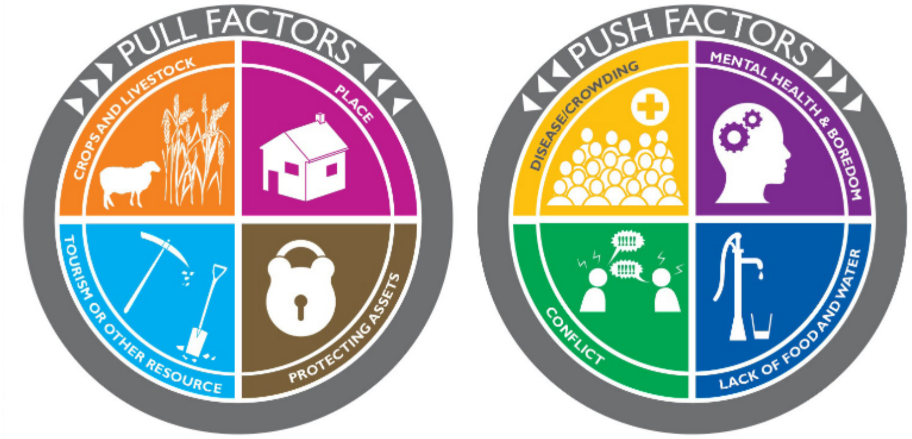

FIGURE 3.3. Main push and pull social drivers of evacuation from volcanic eruption worldwide where information of such drivers was available. From [Barclay et al., 2019].

Conversely, good communication and a shared understanding between different stakeholders may result in a shared commitment to participate in risk mitigation [Andreastuti et al., 2019]. An example of effective collaboration between stakeholder groups comes from Tungurahua, where trust between local *vigías* (watchmen) and scientists permits effective risk communication and evacuation processes [Armijos et al., 2017]. In this case, trust has evolved together with improved shelter conditions, evacuation routes, and resouces together with possibilities for locals to maintain livelihoods inside and outside of the high-risk zone.

3.4.3 Previous studies at Fuego

Although eruptions from Fuego have frequently triggered evacuation and disrupted the lives and livelihoods of local residents, few studies explore the link between volcanic activity and evacuation at this volcano. Early literature focussed on risk through the lens of human and agricultural vulnerability to volcanic hazards [Bonis and Salazar, 1973]. Through recent direct experience, locals were familiar with Fuego's hazards, including pyroclastic flows. Although Fuego had not caused significant damage to surrounding populations, the authors presciently detail possible future losses, the authors penetratingly observed that "the human problems faced by the geologist on the site not only will be repeated, but may be increased manifold in the future" (page 3, Bonis & Salazar (1973) [Bonis and Salazar, 1973]).

Four decades passed between this work and the next similar study [Graves, 2007]. Graves (2007) conducted exploratory qualitative research in communities on Fuego's south-west flanks. She discovered high awareness of volcanic risk coupled with widespread normalization of Fuego's behaviour, and increased volcanic risk awareness with age: “people who lived through the eruption of 1974 have a much more acute vision of the danger of Fuego, whereas the younger women or people new to the village do not have that kind of awareness” (page 48, Graves (2007) [Graves, 2007]).

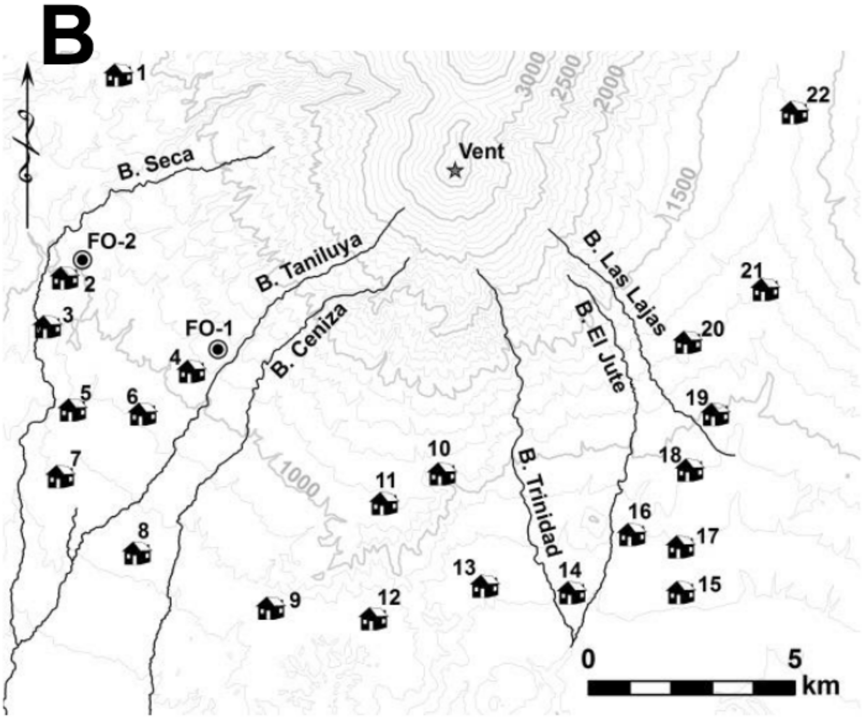

FIGURE 3.4. Locations of various communities around Volcán de Fuego and position of six of Fuego’s seven major barrancas, excluding Barranca Honda (north of Barranca Las Lajas). Figure from Escobar-Wolf (2013). Table 3.2 lists communities included in previous studies of volcanic risk at Fuego, as presented in Section 3.4.3. Numbers are as for this figure.

León Ramírez (2012) studied parameters of vulnerability in the community of Panimaché Uno, and confirmed Graves’ findings of local familiarity with volcanic hazards and awareness of volcanic risk. Nevertheless, the latter did not translate to preparedness: 65% of respondents stated that they would not know what to do in a crisis such as a large eruption.

The most comprehensive study of volcanic risk at Fuego was conducted by Escobar-Wolf (2013) using the Protective Action Decision Model (PADM) to consider situational and perception variables in decision-making during volcanic crisis. This work consisted of a pilot study in 2009 involving 38 individuals that informed a quantitative survey conducted in 2010 with 155

Study	**Community number**	**Community name**
Graves (2007)	2 (FO-2), 4, 6, (not listed)	Sangre de Cristo, Panimaché Uno, Morelia, (Panimaché Dos)
León-Ramirez (2012)	4	Panimaché Uno
Escobar-Wolf (2013)	2, 3, 4, 6, 14, 16, (not listed)	Sangre de Cristo, Palo Verde, Panimaché Uno, Morelia, La Trinidad - 15 Octubre, La Reina, (Panimaché Dos, Santa Sofía)
This chapter	**3, 4, 6, 7, 11, 12, 13, 16, 20, 22, (not listed)**	**Palo Verde, Panimaché Uno, Morelia, Los Yucales, Ceilán, Chu-chu, Guadalupe El Zapote, La Reina, La Reunión, Alotenango, (Panimaché Dos, San Andres Osuna, La Colonia)**

Table 3.2: Table listing communities appearing in this chapter and in previous studies of volcanic risk at Fuego. Numbers refer to community location on Figure 3.4. Numbered communities are listed alphabetically, followed by non-numbered communities.

individuals in 8 communities around Fuego (pages 151 – 152, Escobar-Wolf (2013) [Escobar Wolf, 2013]). These studies showed that locals frequently faced the decision of whether to evacuate or not from an eruption. Factors affecting the decision to evacuate included fear of looting and poor shelter conditions. This study made an enormous contribution towards understanding of population demographics around Fuego, including a summary of the complex origin and development of rural communities from plantations subsequently transformed by resettlement policies following the civil war years (1960 – 1996). While not explored in depth, such information contextualized the (un)willingness of local residents to evacuate their homes due to Fuego's behaviour. Additionally, Escobar-Wolf's study determined quantitatively that locals' willingness to evacuate from a large eruption was influenced by the conditions under which evacuation took place. These conditions included potential loss of livelihood or property and potential hardship faced during the evacuation and in shelters. Escobar-Wolf's work was influential in my research design for my fieldwork seasons in 2018 and 2019. However, his work did not explicitly compare direct experiences of activity between local residents and authorities. This chapter therefore contributes to the debate on eruption and evacuation at Volcán de Fuego through study of comparative experiences to understand the conditions under which evacuation does or does not take place.

Figure 3.4 is a map of communities around Fuego that have been captured by the studies citepd above. Table 3.2 is an accessory to clarify the figure.

3.4.4 Summary and chapter objectives

Risk is not produced the moment a pyroclastic flow descends a volcano's flanks. Instead a complex array of factors, including eruptive history, experiences of previous activity, existing social, economic, political, and structural pressures within different stakeholder groups, and communication between these groups, are interwoven to produce an environment of persistent, dynamic volcanic risk that fluctuates as any of these factors change. Unfortunately, a comprehensive record of such factors is rarely available, even at the most active volcanoes. The lack of published literature on volcanic risk at Fuego in recent (<10) years, while both eruptive activity and risk mitigation efforts have changed considerably, represents a particularly crucial gap in academic knowledge.

Based on existing literature, there are several themes in volcanic risk that if explored at Fuego are likely to make important contributions to academic knowledge. In particular, the influence of livelihoods and of existing social and economic pressures on volcanic risk and local peoples' decisions to reduce this risk (including the decision to evacuate from an eruption) has been little studied at Fuego. Such information is an important academic contribution and has been shown in other environments to be useful in informing risk mitigation policy. Furthermore, literature illustrates that trust between different stakeholder groups has important consequences for volcanic risk: this theme should be explored following the 3rd June 2018 eruption and its impact of local confidence in INSIVUMEH and CONRED. The different fates of people in San Miguel Los Lotes and La Reunion on 3rd June may be related to these socio-economic pressures and to trust in INSIVUMEH/CONRED. Contrasting such fates is important as an intellectual exercise to understand the root causes of vulnerability during evacuation from volcanic crisis.

An additional theme that has been under-explored in existing literature is how different stakeholder groups experience a volcano's activity. This is likely to be a fruitful theme to explore at Fuego, given the extraordinary change in eruptive activity observed since 2015 [Naismith et al., 2019a]. Exploring local peoples' experiences of evacuation is also essential as evacuation is the only risk mitigation policy that is effective against pyroclastic flow hazard. The objectives of this chapter are to explore the above themes at Fuego through, first, gathering local peoples' descriptions of their experiences of past eruptive activity; second, gathering local testimonies of the factors that affect their decision to evacuate from activity of Fuego; finally, to compare these two subjects with descriptions from non-local stakeholders (i.e., INSIVUMEH and CONRED staff) of their experiences of Fuego's activity and of evacuations. The following questions provide direction for these objectives:

> *At Fuego, paroxysmal eruptions represent a large risk that may reasonably be managed by repeated temporary evacuation of communities. How does the change at Fuego presented in Chapter One compare to peoples' experiences of volcanic activity? How important are these experiences in determining peoples' decision to evacuate or not in the new eruptive regime?*

Table 3.3 defines common terms in volcanic risk literature, including the term 'risk perception'. This chapter explicitly studies experience of previous eruptive activity as opposed to volcanic risk perception. This is because, firstly, of a tendency towards the false isolation of volcanic risk perception as the only risk that people face in a volcanically active environment [3]. Instead, "volcanic risk perception should be seen as one among many aspects of people's vulnerability in the face of natural hazards. It is one form of risk perception that is balanced, by individuals with other forms of perception including risks to livelihood and cultural heritage" [Gaillard, 2008]. Secondly, as described by [Haynes et al., 2008], risk managers attempting to understand volcanic risk and its perception among local people have traditionally assumed these people to be lacking in knowledge and suffering a deficit in perception that may be corrected by outside stakeholders possessed of an objective understanding of the volcanic risk. However, the lack of simple association between volcanic risk awareness, perceived risk, and responses among local people in various environments (e.g., Montserrat, Tungurahua, Soufrière Hills) suggests that this deficit model is flawed, and that volcanic risk is inherently subjective. By focussing on experience of previous activity instead of volcanic risk perception, I hope that this chapter provides a more complete contribution to the debate of volcanic risk at Fuego.

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[3] This can be observed by the fact that many studies refer to "volcanic risk perception" as simply "risk perception".

Term	Definition	Source
Awareness	The state or condition of being aware; having knowledge; consciousness.	`https://www.dictionary.com/browse/awareness?s=t`
Evacuation	Moving people and assets temporarily to safer places before, during or after the occurrence of a hazardous event in order to protect them.	UNISDR `https://www.undrr.org/terminology#E`
Experience	Knowledge or practical wisdom gained from what one has observed, encountered, or undergone.	`https://www.dictionary.com/browse/experience`
Hazard (volcanic)	Any potentially dangerous volcanic process (e.g., lava flows, pyroclastic flows, ash).	`http://www.geo.mtu.edu/volcanoes/hazards/primer/`
Livelihood	A means of supporting one's existence, especially financially or vocationally.	`https://www.dictionary.com/browse/livelihood`
Risk (volcanic)	Any potential loss or damage as a result of a volcanic hazard that might be incurred by persons, property, etc., or which negatively impacts the productive capacity/sustainability of a population. Risk not only includes the potential monetary and human losses, but also includes a population's vulnerability.	`http://www.geo.mtu.edu/volcanoes/hazards/primer/`
Risk perception	The possibility people give that a hazard will affect them.	Gaillard (2008)
Vulnerability	The conditions determined by physical, social, economic and environmental factors or processes that increase susceptibility of an individual, a community, or systems to the impacts of hazards.	UNISDR `https://www.undrr.org/terminology#V`

Table 3.3: Definition of common terms in volcanic risk literature and their sources. Note that "Volcanic hazard" and "volcanic risk" are terms frequently confused. A comprehensive discussion of the complexities of these terms can be found at `http://homepages.uc.edu/~huffwd/Volcanic_HazardRisk/Hazard_Risk.html`.

3.5 Methods

This section presents the research methods and practical aspects of data collection for this chapter. In order to study experiences of previous eruptive activity and factors affecting evacuation around Fuego, qualitative data collection methods were chosen because of the flexible and exploratory approach to research they afforded. More specifically, qualitative methods allow the researcher to "better understand [a] phenomenon about which little is yet known … to gain more in-depth information that may be difficult to convey quantitatively" [Hoepfl et al., 1997]. In addition, qualitative research allowed in-depth understanding of the motivations and interactions between different stakeholder groups. I was guided in my choice of methods by volcanic risk literature such as Jóhannesdóttir and Gísladóttir [2010] and Stone et al. [2014].

I chose in-depth interviews as the main method of data collection, similar to Jóhannesdóttir and Gísladóttir [2010]. Interviews allowed me (the interviewer) and my interviewee to generate new knowledge through conversation: in an inter-view, "knowledge is constructed in ... an interchange of views between two persons conversing about a theme of mutual interest". [Kvale and Brinkmann, 2009]. As the authors state, inherent in interviewing is "the dual aspect of ... the personal interaction and ... the knowledge constructed through that interaction" (page 2, Kvale and Brinkmann [2009]). Acknowledging the former aspect involves reflexivity or critical self-scrutiny, which is discussed in detail in this thesis's introduction (See 1). In brief, my position as interviewer at Fuego involved "a move away from the neutral, detached observer that is implied in much classical survey work" [Byrne, 2004] – a starting point that is inherently understood as my position in the first two chapters of this thesis. In this chapter, qualitative research provides interpretative advantages that allow more effective capture of experience, as such data are more easily observed than measured.

The data presented in this chapter were collected in two studies: first, a pilot study involving interviews with INSIVUMEH and CONRED staff in February - March 2018; second, a study of experiences of local people, supplemented by those of INSIVUMEH and CONRED staff, in February - April 2019. Both projects underwent institutional review and were approved by the University of Bristol Ethics Committee (2018 project approval number: 62341, title: "An investigation into hazard preparedness and evacuation procedures at Volcán de Fuego, Guatemala"; 2019 project approval number: 76281, title: "Perceptions of eruptive activity and factors affecting the decision to evacuate among different stakeholder groups at Fuego volcano, Guatemala").

Participants in the 2018 and 2019 projects were recruited by different methods. All participants in the 2018 project were already known to me through previous field visits to Guatemala. All were approached individually and asked to participate given their experience developed through working either in monitoring and analysis of Fuego's activity (INSIVUMEH), or in reducing disaster risk (CONRED). Participant recruitment in 2019 was a more concerted effort. The first 10 days of the nine weeks' fieldwork were spent at INSIVUMEH's Fuego observatory, OVFGO1, to gain familiarity with the community. Being a western outsider and a non-native Spanish speaker, I sought support from a local resident. I hoped that this support would provide me with benefits similar to those that a research assistant provides in ethnographic research, in facilitating access to research participants and encouraging acceptance of the researcher in the communities under study [Donovan, 2010]. I found this support in the form of Edgar Antonio Escobar Barrios, a resident of Panimaché Uno and an observer at INSIVUMEH's OVFGO1 in that community for 16 years. Edgar is respected in his community for this work and also maintains frequent contact with other communities in the region through regular talks on Fuego's activity and social projects such as the distribution to communities of food donations from NGOs following the eruption of 3rd June 2018. He was a trustworthy and patient companion during my research in communities on Fuego's western flanks, frequently assisting in translating nuances of language and greatly assisting my research goals. In communities on the eastern flanks, I was initially accompanied by a colleague from CONRED's UPV office, but for later interviews I went into the field alone. All efforts were made to minimize the effects on interviews of having a field assistant. In the field, I travelled between rural communities in a hired red Mitsubishi L200 truck ("El Corazón") with vulcanized tyres. Despite the short duration of the fieldwork, there was value in repeating visits to acquaintances and requesting an interview after several meetings. Local people interviewed in 2019 were recruited through a mixture of purposive sampling [Palinkas et al., 2015], where knowledgeable individuals were approached for interview, and 'snowball' sampling [Bryman, 2016], where initial interviewees would recruit further participants. Interview data was supplemented by participant observation, a form of non-intrusive data collection involving observing and participating in community activities [Bryman, 2016].

	Characteristic						
	Sex		**Age**				
	Male	Female	18 - 29	30 - 39	40 - 49	50 - 59	60+
Count	14	21	5	6	10	8	6

	Characteristic									
	Location									
	AL	CL	CC	LC	LR	LY	MO	PD	PU	SO
Count	1	3	1	1	1	6	6	2	11	3

Table 3.4: Demographic data of local people who gave recorded interviews during 2019 study. People under 18 years old were not invited to participate due to additional ethical approval requirements. Initials for locations are same as for Figure 3.5. Note that number of participants in this table (n = 35) does not match number of recorded interviews with locals (n = 32) because three interviews contained two participants.

Most local residents who were invited to interview were willing to participate. The short length of my field season in 2019 prevented some interviews from taking place. Approximately 60 people were approached for interview. In total, 41 interviews were completed, of which 37 were audio-recorded. The 37 included 32 interviews with local residents on the slopes of Fuego, held in nine communities and a golf resort near the volcano (Figure 3.5). These communities are found in three departments of Guatemala: Chimaltenango (La Colonia, Los Yucales, Morelia, Panimaché

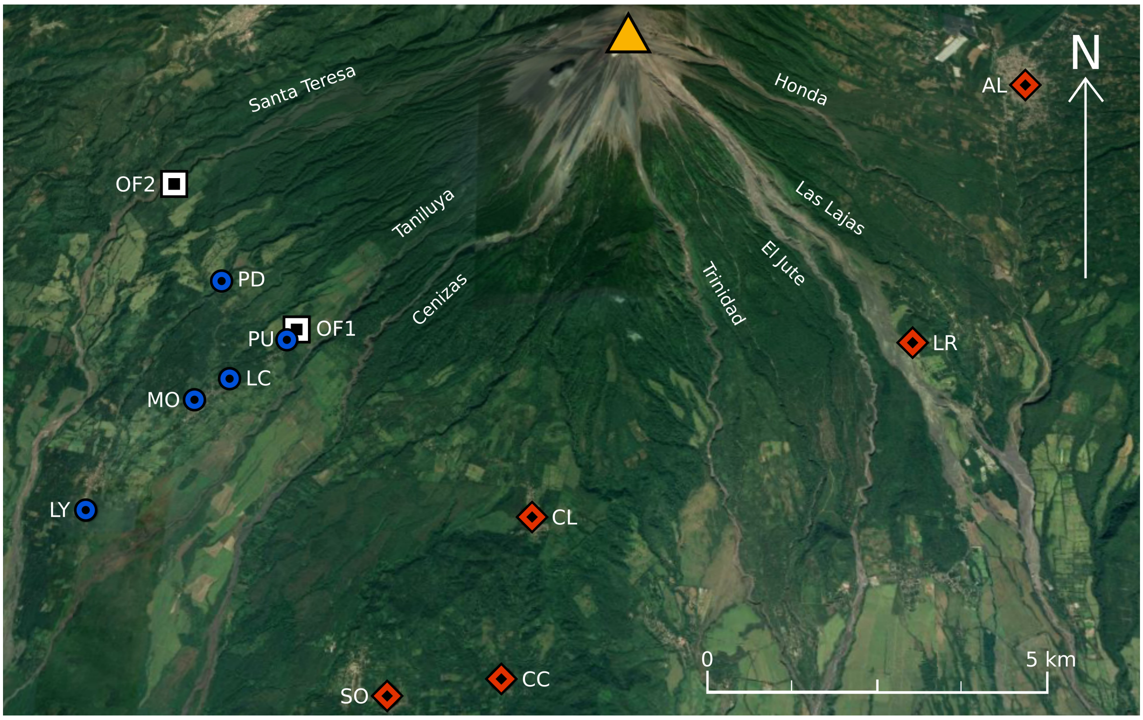

FIGURE 3.5. Map of locations visited at Fuego in 2019. Blue circles represent western communities: LC (La Colonia), LY (Los Yucales), MO (Morelia), PD (Panimaché Dos), PU (Panimaché Uno). Red diamonds represent communities further east: AL (Alotenango), CC (Chu-chu), CL (Ceilán), LR (La Reunión), SO (San Andrés Osuna). White squares represent INSIVUMEH observatories: OF1 (Panimaché Uno) and OF2 (Sangre de Cristo, permanently evacuated since June 2018). Large yellow triangle represents summit of Fuego (3763 m). Barrancas are labelled.

Dos, Panimaché Uno), Escuintla (Ceilán, Chu-Chu, San Andres Osuna), and Sacatepéquez (Alotenango, La Reunión). Staff from INSIVUMEH and CONRED were interviewed in Antigua, Alotenango, and Guatemala City. In order to preserve confidentiality these people are referred to as “Official” when quoted. Due to time constraints, no people aged >50 were interviewed from communities in Escuintla or Sacatepéquez. Table 3.4 gives demographic data of local people who gave recorded interviews in 2019. Livelihoods of 35 local residents included in Table 3.4 are as follows: 16 residents were housekeepers, 4 were business owners, 3 worked in agriculture, 3 were retired, 3 worked in education, 2 worked in management, 2 worked for the municipality, and 2 were unemployed (n = 35).

Interviews were held in Spanish. Because some local residents were not literate, I obtained verbal consent before starting an interview. I sought permission to record the interview from the participant(s) involved. I also explained to participants the purpose and expected length of the interview, clarified that any information they provided would be treated confidentially, and invited them to inform me if at any point they wished to stop the interview. Some people were wary of appearing ignorant when discussing a volcano with a volcanologist. To counteract this, I explicitly stated that I wished to hear experiences of the volcano from those who had knowledge that I did not. After the interview, I invited the participant(s) to contact me if they had further questions or requests. To facilitate this, I provided a small piece of paper with my photograph and contact details (Figure 3.6).

Mi nombre es Ailsa Naismith. Soy estudiante de doctorado de la Universidad de Bristol en Inglaterra. Estoy haciendo un proyecto sobre el Volcán de Fuego y las personas que viven en sus faldas. Me interesa conocer sus experiencias de la actividad volcánica, y entender la relación que tienen las personas con el volcán.

Le agradezco mucho por su interés y participación en este proyecto. Toda información que usted me comparta será tratada con mucho respeto y en confidencialidad. No voy a utilizar nombres en los informes escritos ni en presentaciones. Me puede contactar por:

Numero de teléfono: +502 4856 8752
Correo: ailsa.naismith@bristol.ac.uk

FIGURE 3.6. Debriefing sheet with contact details given to people who had participated in the 2019 study.

Both the 2018 and 2019 projects involved the use of questionnaires. Questionnaires are a useful research tool to explore experiences of activity and volcanic risk. Additionally, they provide information of public knowledge of natural hazards that can inform the development of risk mitigation solutions [Bird, 2009]. Nevertheless many volcanic risk studies do not fully disclose the details of the questionnaire that delivered the results they present; adequate descriptions should include: “response format (open/closed questions), mode of delivery, sampling technique, response rate and access to the questionnaire to allow reproduction of or comparison with similar studies” [Bird, 2009]. For clarity, I have provided all such details. I used questionnaires structured as a series of open questions categorized by theme. Questionnaires can be found in Appendix D (Chapter 9). I allowed interviews to deviate from the structure to explore potentially interesting deviations. Interviews were recorded with an Olympus WS-853 digital voice recorder. After each interview I immediately wrote up notes in my field notebook, and each evening I assembled this information by adding notes and demographic data of that day’s interviewees to a master Excel spreadsheet. I then began manual transcription by creating a Word file and including interview data.

The circumstances of daily life in communities around Fuego were unpredictable, so that many interviews were conducted in unusual or spontaneous circumstances [4]. I might conduct 4 – 5 interviews in a single day, then not have another opportunity in the next week. Intervening time was used to (1) gather additional data through participant observation; (2) take notes in my notebook, a constant companion and place for reflection; and (3) perform initial analysis of interview data.

Interviews were manually transcribed into written Spanish using OTranscribe and HappyScribe software. I completed this process in Bristol in August 2019. The interview transcripts were loaded into NVivo software, which functions in both English and Spanish. NVivo was used for thematic analysis of interview transcripts to generate "codes", units of meaning in the data that had potential analytical significance. Interview material was analyzed inductively, allowing themes to emerge and be evaluated in the manner described by Creswell (2014): “inductively building from particulars to general themes, and ... making interpretations of the meaning of the data.” [Creswell, 2014]. This inductive approach to thematic analysis was informed by Pistrang & Barker (2012) [Pistrang and Barker, 2012]. To distinguish the most significant themes, interview transcripts were coded iteratively, meaning that inductively derived codes were applied to transcripts and field notes, which were then re-read and analysed to generated additional codes [Ritchie, 2003]. Although time-consuming, the process was effective in producing robust themes through its “resolute ... slow intensity” (Maclure, 2013) [Maclure, 2013]. Initial codes were generated from a reference library and from word searches using in-house query tools. These included single-word codes (e.g., *‘evacuación’* or ‘evacuation’) and phrase codes that referenced local experiences (e.g., ‘Oct 1974’). The full process allowed identification of the themes that are the main results of this chapter. These themes include: a disparity between communities on Fuego’s east and west flanks in terms of memories of previous eruptions and communication with INSIVUMEH and CONRED; effects of experiences of the 1966 and 1974 eruptions on peoples’ responses towards recent activity of Fuego; and vast differences in the way locals and non-locals focussed attention on eruptive activity at Fuego. Quotations that illustrate these themes have been translated from Spanish and included in the following section along with their position at Fuego (west or east flanks) to validate the results. Further validation was achieved through triangulation of themes between the different data sources of in-depth interviews, "conversations with a purpose", and participant observation, similar to triangulation achieved by Stone et al. [2014].

3.6 Results

This section explores key themes that emerged through analysis of interviews and observations gathered in 2018 and 2019. Interviews were analysed with the aim of answering the questions presented in this chapter’s introduction, namely: How does the change at Fuego presented

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[4] One memorable interview took place in a primary school classroom while eating *chocobananos*.

in Chapter 2 compare to peoples' experiences of volcanic activity? How important are these experiences in determining peoples' decision to evacuate or not in the new eruptive regime? Initial analyses were performed using NVivo's in-house analytical tools. Results from these initial analyses appear in Appendix E (Chapter 10). Main themes generated by iterative coding sessions are summarized in Table 3.5. Results follow in the same order presented in Table 3.5.

Theme	Subtheme
Direct experience of previous eruptive activity	1. Differences in focus 2. Significance of previous large (VEI ≥ 2) eruptions 3. Local experiences of specific volcanic hazards
Factors affecting evacuation	5. Trust between stakeholder groups 6. "Push" and "pull" factors 7. Responsibility for decision-making and self-evacuation policy

Table 3.5: Key themes explored in results produced from 2018 and 2019 fieldwork.

3.6.1 Direct experience of previous eruptive activity

3.6.1.1 Differences in focus

Interviews in 2019 revealed significant differences between locals' and authorities' direct experience of previous activity of Fuego. The change in Fuego's behaviour presented in Chapter 2 does not agree with local peoples' experience. Locals have noticed an increase in Fuego's activity since 1999, with descriptions of "increase in rumbling" and "the volcano making noise" since that time. However, local residents have neither observed nor experienced the rapid increase in paroxysms from 2 – 4 per year between 1999 and 2014 to 12 – 16 per year since 2015. When asked how many eruptions had occurred within the past five years, locals frequently estimated a number lower than ten. On several occasions when interviewees were asked about a specific paroxysm, they replied that it did not happen. For example, when questioning a woman from Panimaché Uno on the paroxysm of 31st January – 2nd February 2018, she replied that the only paroxysms to have occurred in the last two years were those of June and November 2018. In contrast, INSIVUMEH recognized four paroxysmal eruptions in 2018: those beginning 31st January, 3rd June, 12th October, and 18th November. Locals describe Fuego as persistently active, with flares of activity set within periods of calm. Smaller eruptive events in 2015 – 2018 that are reported as paroxysms by INSIVUMEH are seen by locals as periods of unrest only. Locals describe these periods as "thunder" or "rumbling". They refer to only the largest paroxysms (e.g., September 2012, June 2018) as "eruptions". While locals in communities around Fuego consistently remembered large eruptions in 1999, 2012, and 2018, the eruptions of 2007 and 2017 were remembered most clearly by locals living on Fuego's western flanks. In fact, Fuego's 2007 eruption motivated a practice of repeated self-evacuation in the community of Sangre de Cristo (see Section 3.7.2.1). Implications of geographical differences in locals' experiences of previous eruptions are explored in Sections 3.7.1.2 and 3.7.2.1. Locals often connected descriptions of eruptive activity with a sense of having become accustomed to the activity. This was true of activity they experienced both before and after 3rd June 2018. The resident below speaks of activity after June:

> Resident of Panimaché Dos (West):
> Sometimes we think it's only going to make rumbles again, or ash fall, or a bit of *arena* will fall, and then it'll pass. So, that has allowed some of us to stay here. We are already used to the rumbles and we have this already as an experience – that the rumbles don't scare us any longer, nor do the flares of fire that appear each night.

When I asked local people about previous eruptive activity of Fuego, they classified only the largest paroxysms since 1999 as "eruptions". Local people did not distinguish between Fuego's activity pre- and post-2015 and this was consistent across age and location. By contrast, INSIVUMEH and CONRED staff observed a change in Fuego's activity similar to Chapter 2 results:

> Official 1:
> And then we arrived in 2015, when the eruptions were very frequent, almost every 20 days. 15, 20 days, there were eruptions with pyroclastic flows, effusive ... in 2015 there were 15 eruptions, in 2016, 16 eruptions. In 2017 the number had dropped already, 9 in the year, and, and ... but including a very large eruption in May 2017 ... So we are waiting, see, to see what will happen. Because just as it changed in 2015, there could be another change so the activity decreases again, to how it was before. But it's still uncertain, how can we know what will happen?

Figure 3.7 illustrates the difference between observations by local residents and by satellite of Fuego's activity in the period 1999 – 2019. Official descriptions of activity closely mirror satellite observations, particularly since 2015, as described in the quotation above. All eruptions illustrated by orange arrows resulted in widespread evacuations of local communities (pg. 74, Escobar-Wolf, 2013). Figure 3.7 contrasts the observations to show that both local and scientific observations are valid experiences of previous eruptive activity of Fuego. Discussion and interpretations of this figure appear in Section 3.7.1.1.

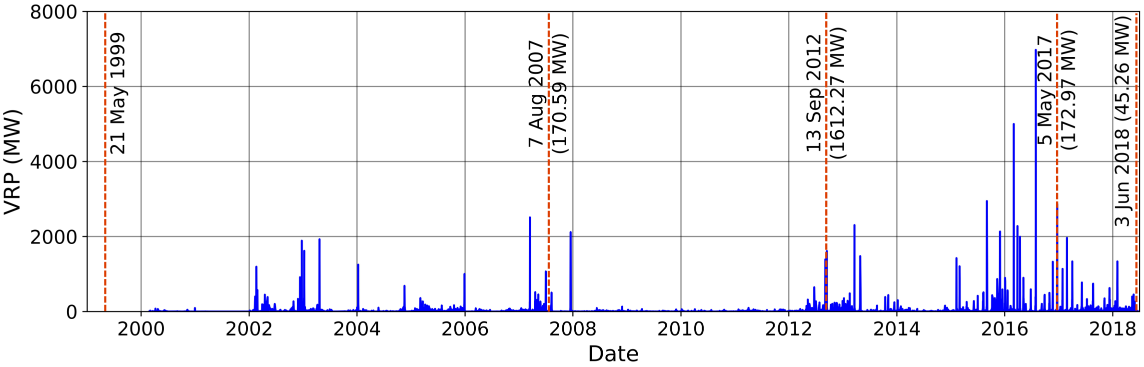

FIGURE 3.7. Contrasting local experiences of eruptions with satellite remote sensing observations. Orange dashed lines represent local experiences of major eruptions 1999 – 2019, while blue lines represents satellite-based thermal timeseries data derived from MIROVA night-time values of Fuego activity 2000 – 2018 (adapted from Naismith et al., 2019). Each one of the eruptions highlighted by locals is associated with largest MIROVA value for that eruption, where possible.

3.6.1.2 Significance of previous large (VEI 2+) eruptions

How important is past experience in determining present position? Locals remember two major eruptions of Fuego in the 20th century: one sometime in 1966 or 1967, and the VEI-4 eruption of October 1974. The Smithsonian recognizes three eruptions of Fuego in 1966 - 1967: February 7th - May 1st 1966 (VEI-3), August 12th - 13th 1966 (VEI-3), and April 22nd – 24th 1967 (VEI-2) [Venzke, 2013]. While local opinion differed on the exact date of the eruption, all accounts describe it as extremely powerful, ejecting an unprecedented volume of material and devastating surrounding forest for many kilometres. Comparing descriptions with photographs (e.g., Figure 3.8) suggest that locals (such as the resident below) remember the eruption beginning in February 1966.

> Resident of Morelia (West):
> So, we were playing marbles ... when it made the rumble, the thunder, like a bombshell. And it rose like a mushroom, a rising bubble, and it spread. And at that moment the rays of the sun were obscured, and we remained in darkness. Only 15 minutes from the start of the explosion, 15 minutes and we were blind ... it was totally destroyed. The houses fell, the rivers ran dry ... and the *arena* fell, fell, fell, and lots of lightning, a lot of friction in the atmosphere, the clouds. ... and any trees which were still half alive were killed by the lightning. And all of the vegetation died. All of it.

All locals interviewed in 2019 who had experienced the 1966 eruption also lived on the west

FIGURE 3.8. Vigorous eruptive column above Fuego's summit, April 1966.

flanks of Fuego, in the communities of Morelia, Panimaché Uno, and Panimaché Dos (Figure 3.5). Older locals in these communities distinguished clearly between 1966 and 1974 in their descriptions: "after that one, another eruption came". Interestingly and in contrast to 1974, the impacts of Fuego's 1966 eruption on these communities have not previously been reported. Nevertheless, many locals insist the 1966 eruption was particularly devastating:

> Resident of Morelia (West):
> The sad thing is that generation – my generation ... until 2000, from 66, until 2000, lost any agriculture. Because now no-one could farm. No-one could harvest anything because nothing would grow. And we tried it, those of us who were already farmers, we tried. It didn't work. And those who were born in a land which is not for farming ... they did not learn anything. Here nothing was produced and the easiest thing is to leave.

It was not possible to meet anyone on the east flanks of Fuego who had directly experienced either the 1966 or the 1974 eruption. However, several residents of Ceilán shared their ascendants' experiences of 1974, talking of fall of rocks 3" in diameter, and a descending darkness that caused the blinded birds to fly into trees in confusion. The fact that these stories have been passed down through generations shows that large eruptions form a key part of eastern local residents' previous experiences of Fuego's activity. However, these experiences spoke of a short, intense eruption. Communities on Fuego's eastern flanks did not in general evacuate [Escobar Wolf, 2013]. Descriptions further west emphasise the significant impacts that followed the eruption.

These include evacuations lasting weeks or months, the death of much of the native forest and wildlife, and the damage to soil that has left a lasting legacy among those that draw a livelihood from agriculture in these communities:

> Resident of Panimaché Dos (West):
> That time the volcano started to – to, as if it were splitting apart. Yes, like this – *Fu! Fu!* – like that. Just like that, and then it paused a little. And continued again. And after a longer pause began again eagerly . . . it thundered and then was silent again. After a while, another. The second time is when it emptied. It emptied itself, and in Los Yucales this depth [indicating a metre] of *arena* came. . . . And where the *arena* had fallen everything remained in silence, these trees over there didn't stay like that. They were all spindly. A total desert.

This person experienced major impacts associated with the October 1974 eruption: they described to me their emergency evacuation and spending weeks living in shelter. By contrast, residents on Fuego's eastern flanks were less affected by 20th-century eruptions:

> Resident of Ceilán (East):
> Interviewer: I was going to ask about your grandparents – did they ever talk about the volcano? Was it active in their time, too?
> Resident: Ah, yes. According to their stories, in their time the volcano also erupted. At the last minute, they had to – climb to the summit of that mountain over there, it wasn't like now, like how the volcano presents itself. Before it was less.

Even in 2019 the impacts of these eruptions remained: while locals on Fuego's east flanks stated, "the land here is very good land", western locals agreed that to find good land one had to dig. A resident of Morelia explained, "the volcano brings more poverty . . . one has to make a hole to [one metre] depth, to reach the good soil."

Experiences of western locals in 2019 are consistent with existing literature on the 1974 eruption, including isopach maps showing principal tephra deposition towards the SW of Fuego (Figure 3.9). Locals use the term *piedra* ("stone") to describe tephra fall in 1974. Size cannot be quantified precisely through description, but the use of *piedra* alludes to the eruption's severity. This is also true of the term *arena* ("sand"), which accumulated to a much greater depth in western communities (Table 3.6: compare 3" (7.6 cm) in Ceilán with 50 – 100 cm in Los Yucales). These terms have been left untranslated in following quotations to preserve accuracy.

Many locals state that the 3rd June 2018 eruption was the largest that they had experienced. In Section 3.7.1.1 I reported that in 2019 I found that locals had become accustomed to activity both before and after June 2018. Local residents interviewed in 2019 gave different dates for the eruption: some recalled it happening in June or July 2018, others recall it was "several (3 - 4) months ago" in February 2019. The latter estimate would correspond to the eruption of 18th November 2018, which was marked by powerful incandescent fountaining at night and evacuation of local communities. However, locals' descriptions of eruptive activity feature an obscuring darkness during the day, which is more consistent with the June 2018 eruption. The 3rd June 2018 eruption was described as singularly powerful by all on Fuego's eastern flanks, who had less prior experience of severe eruptive impacts:

> Resident of Ceilán (East):
> At eleven, twelve ... It started to throw out ash over here, and it started to get darker, and darker, and darker . . . and after it had got pretty dark over here, the electricity went . . . the signal, everything. And the news started to arrive. ... [the eruption] began in the morning. Morning. And it was completely cloudless in the morning. But the error . . . was that this [activity] was already typical for us, we didn't give it much significance. Because we were already used to seeing this . . . it's common. It's going to throw out lava again. It's ordinary. It's already throwing out ash. Everyone who has their crops up there, towards the main square, ash is going to rain on them. Normal.

Many people in western communities agreed that June 2018 was one of the largest eruptions

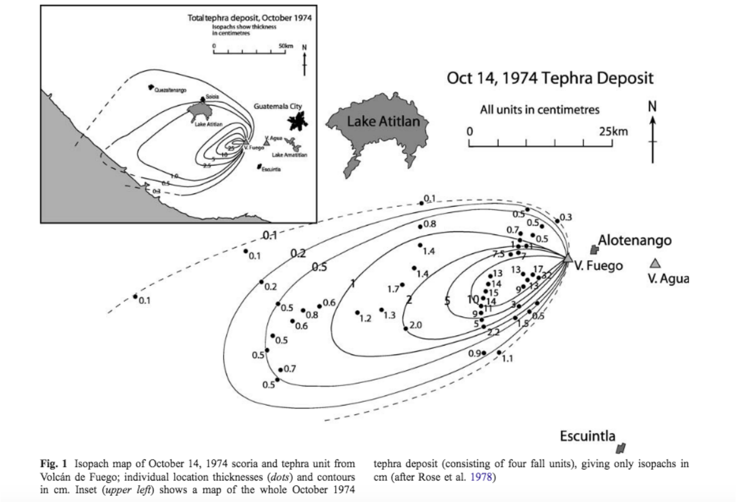

Fig. 1 Isopach map of October 14, 1974 scoria and tephra unit from Volcán de Fuego; individual location thicknesses (*dots*) and contours in cm. Inset (*upper left*) shows a map of the whole October 1974 tephra deposit (consisting of four fall units), giving only isopachs in cm (after Rose et al. 1978)

FIGURE 3.9. Isopach map of deposits from the October 14th 1974 deposit, clearly showing the predominant direction of deposition towards the SW. From [Rose et al., 2008].

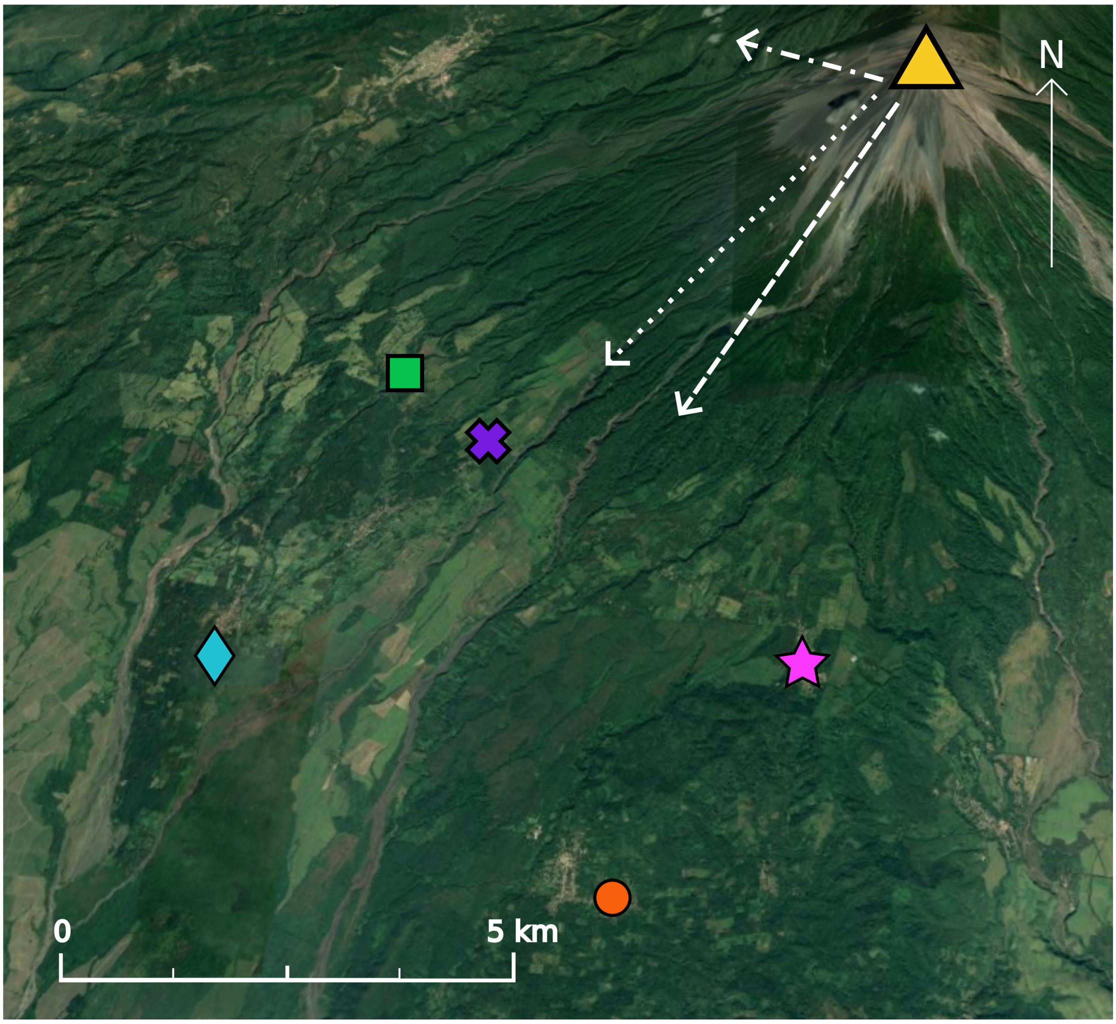

FIGURE 3.10. Local descriptions of tephra fall from the 1974 eruption. Symbols describe local communities: pink star (Ceilán), blue diamond (Los Yucales), green square (Panimaché Dos), purple cross (Panimaché Uno), orange circle (San Andres Osuna). Large yellow circle is summit of Fuego. Arrows represent wind directions of the October 14th 1974 eruption and show predominant wind direction towards WSW. Lines represent altitudes: dashed (4000 m altitude at 215°), dashed (10000 m at 225°), dot-dash (7000 m at 285°). Wind directions from Figure 4 of [Rose et al., 2008]. Locals' verbatim descriptions of tephra fall are found in Table 3.6.

Community	Symbol	Distance (km, direction)	Side (E /W)	Description (English)	Description
Ceilán	**pink star**	8.5 S	E	*"tres pulgadas de arena"*	"three inches of sand"
Los Yucales	**blue diamond**	12.3 SW	W	*“llegó un metro de arena”, “cayó piedras de 3 cm”, “50 cm de arena”*	"“a metre of sand came”, “rocks of 3 cm fell”, “50 cm of sand”
Panimaché Dos	**green square**	8.2 SW	W	*“dos metros de arena”, “cayó piedras de 10 cm”, “Casi topaba la arena, y había que entrar agachados para el corredor”, “había subido casi un metro de arena”*	“two metres of sand”, “10 cm rocks fell”, “the sand almost overcame us, and one had to enter the corridor bent over”, “almost a metre of sand had piled up”
Panimaché Uno	**purple cross**	7.8 SW	W	*"piedras", "arena"*	“rocks”, “sand”
San Andres Osuna	**orange circle**	11.90 S	E	*“cayó arena”, “muchas piedras pero piedras pequeñas”*	“sand fell”, “rocks fell, but they were small rocks”

Table 3.6: Community descriptions of tephra fall associated with the October 1974 eruptive episode. Distance column measures distance in km from summit of Fuego. For location of each description see Figure 3.10.

they had seen. However, a notable exception was among older people in these western communities. They agreed that the 2018 eruption was smaller in scale and in impact than those they had experienced in 1966 and/or 1974. They remarked on the difference in ash fall: *arena* or *piedra* in 1966 and 1974, and *ceniza* (“ash”) in 2018. Here a resident explains the different severities of eruption they experienced:

> Resident of Morelia (West):
> Resident: So that is the fear that we have. But I tell people, “You are all afraid of what the volcano is doing now, this is nothing!”, I tell them.
> Interviewer: “This is nothing”? So – lately, this is nothing?
> Resident: Yes. But these that are – these eruptions are nothing compared to what I have lived, I tell them. Believe me that I, the day of that eruption, when everything went dark, a lot of *arena* fell. After that came another eruption. In which the *arena* was not fine sand so much as fine rocks.

Older locals considered the 2018 eruption minor compared to 1966/1974, and therefore did not evacuate in 2018. Another theme in the responses of older locals was in how they determined eruptive severity. Several stated that their response to an eruption is determined by the type of ash fall:

> Resident of Los Yucales (West):
> I stayed and set to thinking. I told them, "No". I told them, "No. Here ... don't be afraid, my children, because this is *ceniza*. When *arena* falls, yes. When that happens, we must leave."

This resident described in detail that their decision to evacuate would be influenced by the type of ash that fell. If it was fine *ceniza*, the eruption was not severe enough to require evacuation. When fall material was similar to the *arena* that fell on western communities in 1966 and 1974, this would indicate evacuation was necessary.

3.6.1.3 Local experiences of specific volcanic hazards

Previous authors [Graves, 2007, Roggensack, 2001] state that locals are knowledgeable of Fuego's hazards. This was still true in 2019. Locals were familiar with frequently-occurring hazards: many distinguished between different types of ash fall (*ceniza* vs *arena*, as described above) and clearly described the effects of ash on crops, roofing, and respiratory health[5] Residents also described lahars in detail. Locals appeared knowledgeable of the entire narrative of hazards such as ash, including cause and effects: they cited the volcano as the source, described travel of ash from the mountain towards the community, and explained its effects on health when falling. Nevertheless, there were some points on which locals were less certain. At Tungurahua scientists and locals have developed a shared language that allows them to communicate clearly ([Armijos et al., 2017], allowing for a shared responsibility in dealing with eruptive activity. In contrast there are clear differences in how locals and officials describe Fuego's hazards that indicate an absence of such shared responsibility. At Fuego, locals use the word *lava* to describe a variety of volcanic flows, including lahars, pyroclastic flow, lava flow, and incandescent ballistic fountaining visible at night. It is therefore difficult to characterize a specific hazard from description alone. For example, a local describes a flow from the 21st May 1999 eruption:

> Resident of Panimaché Uno (West):
> There was – a current passed. We went running to see it. To which my father said,

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[5] An interesting deviation appeared from an interview with a resident of La Colonia. This resident voiced concerns of damage to roofing ("la lamina") from ashfall. This resident was also the only study participant who had a definitive theory for the cause of Fuego's eruptions: "cuando empiezan todos los fuegos ... el Señor nos va otra vez". Why? "Por allá, en los E.E.U.U., un hombre se puede casar con un hombre - que decía usted, si viera estos dos hombres así casados?". Fortunately, I did not find any other residents who shared this belief.

> "That, that lava which, that current which is coming down", he said, "in front of it a lava is coming". Because in front one could see – a black, black *humazón* [cloud of smoke]. Which was sending up steam, when the water was already going. Think of – if you have a little hot ash, and you pour ice water on it, the steam rises eagerly. A-ha. It was like that. Because it went on rising like that, that was how it appeared. We went to see, but at the same time we held back, because it scared us.

Several factors suggest the hazard this resident witnessed was a lahar. Firstly, the use of the word 'current' describes a fluid flow; the description of steam rising from the flow is consistent with field observations of lahars at Fuego; finally, the proximity of the witnesses to the *barranca*, coupled with their subsequent lack of injury, make it less likely that the hazard was a pyroclastic flow. Nevertheless I remained uncertain of the exact hazard this resident observed: it is possible the hazard was a pyroclastic flow, or even a non-volcanic current. The lack of a specific word to describe pyroclastic flows contributes to create uncertainty of local residents' descriptions of volcanic hazards. This lack is possibly because prior to June 2018, many locals had not experienced a clear example of this hazard. When they could be distinguished as such, local descriptions of pyroclastic flows during my 2019 fieldwork were often identified by reference to the mass and colour of the hazard, and triangulated with other sources that confirm the occurrence of pyroclastic flows on that occasion, as illustrated by this local's description of pyroclastic flows on 3$^{\text{rd}}$ June 2018:

> Resident of Ceilán (East):
> At eleven, twelve [o'clock], we began to see that it started to throw out more, as if it were smoke. We said, "Ah! What a *humazón* it's throwing out towards the other side!". But we didn't know the name of the material it was erupting. And from then on, from midday onwards, we saw that it started to throw out material this side too. . . . But we saw that all this side of the volcano, towards the side with Los Lotes, we saw it as smoke, that is how it came. As if it were an enveloping ball. As if it were a ball of gas. [The town] was buried like that.

3.6.2 Factors affecting evacuation

3.6.2.1 Trust between stakeholder groups

Communities around Fuego in 2019 had inconsistent levels of trust in authorities, with local opinion varying between complete faith in authority and total self-reliance. This variability was most clearly expressed in a striking difference between communities on the west and east flanks in terms of their communication with INSIVUMEH and CONRED. The presence of INSIVUMEH-owned observatories in Panimaché Uno (OVFGO1) and Sangre de Cristo (OVFGO2, until June 2018) (see Figure 3.5), and the regular visits of INSIVUMEH scientists from Guatemala City, builds confidence between western locals and INSIVUMEH. . Western locals appreciate the presence of the observatories and INSIVUMEH's role in issuing information during volcanic crisis. These factors have generated so much trust between locals and observers that some locals believe INSIVUMEH carries the responsibility for preparedness for an eruptive disaster. Many locals in the west, when asked about their decision to evacuate or not, stated that they could not distinguish when the volcano was becoming dangerous, and that they relied on advice from "up there" (OVFGO1 in Panimaché Uno) to tell them when to evacuate:

> Resident of Panimaché Uno (West):
> Interviewer: And how did you know? What was the alert, the information?
> Resident: Because it came from INSIVUMEH up there. They advised us. They gave the alarm that we had to leave, so we got together in order to leave. They alert us in case we have to leave. If they don't advise anything, we do not leave. If the volcano is erupting, and they don't advise us, we don't leave. While they – we wait for their voice in order to leave.

In contrast to the good relationship between locals and INSIVUMEH/observers, western locals' interactions with CONRED were less positive. Several residents stated that CONRED rarely came to provide training or information. The opinion below was strong but not uncommon:

> Resident of Panimaché Uno (West):
> CONRED, their area, supposedly their work is to look out for the communities, give talks, so that disasters don't happen. Right? But always, as I said, CONRED never come to give talks. You've seen now that – that CONRED said, "One week on this side of Fuego, one week on the other" – and see, then, four weeks and they haven't come. They are always like this . . . they always fall short.

Residents of eastern communities were far less familiar with INSIVUMEH. They had neither an observatory nor familiar faces with which they could associate INSIVUMEH's work. Instead they knew CONRED through its sub-department UPV and their frequent visits to local COLREDes. Figure 3.2 gives an overview of how these groups communicate during activity of Fuego. COLREDes on the east flanks of Fuego include volunteer participants who perform similar roles to observers at Panimaché Uno, acting as knowledgeable and trusted voices who inform others of changes in eruptive behaviour and co-ordinating community response when Fuego is more active:

> Resident of Ceilán (East):
> I – as I said, I work here in the COLRED for my community. [That time] I noticed the wailing. People were saying, "And when will we leave? What is going to happen to us?". And I said . . . I have an example. One day – about three days after the tragedy, I was

> here living through difficulty. Take it from me, I had never lived through something like that, here on the side of the – and a woman called, "[Resident's name]! Over there you can see the lava! What should we do?". And I – with my training, I told her, "Well, let us leave, over there are my associates."

While western locals' trust in INSIVUMEH and its observers is evident, the level of confidence of eastern locals in their COLRED was less clear. I observed that the organization and size of a COLRED is highly variable between communities and subject to rapid, unexpected change: in the nine weeks' duration of the 2019 study, at least two COLREDes were restructured. Motivation appeared higher among COLRED volunteers who host a community's radio: many residents stated that being chosen to host and operate a radio base was a source of pride. However, the politics of owning a radio are complicated. In several communities, ownership disputes have led to a breakdown in communication, either within the COLRED or between the COLRED and UPV. Happily, this difficult situation appears to be improving. In 2020, communication between 27 communities is regularly maintained, with reports of eruptive activity being shared four times daily (W. Chigna, pers. comm.). Participation in COLRED is a voluntary, unpaid role, and in 2019 many locals expressed that they were disincentivized to participate. This was partly due to a lack of recognition of the role from their community and partly due to inconsistent support from UPV. In 2019 I found that several COLREDes had infrequent contact with UPV and received little information or support from this entity that supposedly acts as advisor to, and co-ordinator of, COLREDes. One local expressed this sentiment elegantly: "Why should we continue, when no side supports us?".

3.6.2.2 "Push" and "pull" factors

Socio-economic factors dominate over hazard adjustment in driving decision-making in areas of high volcanic risk [Gaillard, 2008, Barclay et al., 2019] (see Figure 3.3). The same is true at Volcán de Fuego. In communities around the volcano that mostly rely on agriculture for livelihoods, care of livestock is of high priority, and losses in this area keenly felt: a resident formerly of Sangre de Cristo recalls the eruption of 5th May 2017 because the community lost several cattle from injuries associated with ash fall. Shelters recently built to house livestock during eruptive crisis in Panimaché Uno and Panimaché Dos could support locals who wish to evacuate by securing livestock wellbeing and thus removing a barrier to evacuation. However, even by removing a barrier to locals' desire to evacuate, there is a possibility that local tolerance for evacuation would last only days [Barclay et al., 2019], and people at Fuego may return prematurely to high-risk zones.

Smaller animals are also sources of concern for locals at Fuego: chickens must be cared for, and beloved domestic pets are difficult to evacuate. People expressed great worry about their domestic possessions and the possibility of looting. Many stated that 'other people' outside their community would take advantage of an evacuation by exploiting the absence of villagers to enter houses and rob them. While this is a common theme in volcanic risk literature (e.g. Barclay et al. [2019]), this study presents the first evidence of this occurring at Fuego. It confirms the importance of hearing local voices in the discussion of volcanic risk:

> Resident of Panimaché Dos (West):
> Resident: But the surprise was that after 15, 20 days, my father returned with my older brothers, but they had already – they had already entered the house. And they had stolen all the things we'd left, because that time we left with only the things we carried. And coats, the good clothes, all this they had stolen.
> Interviewer: And this was – sorry, the same – in 1974?
> Resident: Yes. Because since most people had left, some remained behind to sack the houses. So that was the reason my father didn't want to leave.

In many communities like Panimaché Dos, an evacuation plan has been developed that encourages early evacuation of women, children, infirm, and the elderly, while able-bodied men stay behind to secure houses and to sweep roofs of ash. Both locals and officials expressed dissatisfaction with this "imperfect" action plan. Nevertheless, local belief is that this plan minimizes danger to life while ensuring protection of community resources. This strategy could thus be reframed as 'minimization of risk' [Barclay et al., 2019] and an effective way of coping with volcanic risk at Fuego.

Another important issue at Fuego is the conditions of evacuation shelters. Tobin & Whiteford (2002) [Tobin and Whiteford, 2002] state that evacuation effectiveness is partly dependent on shelter conditions relative to domestic ones. At Fuego, poor evacuation shelter conditions had dissuaded several people from evacuating in subsequent crises:

> Resident of Panimaché Uno (West):
> Well, when they take us there, to Santa Lucia, there they leave us in the schools. And there everything is ... how should I say it? That they pile the people up, and the bathrooms are very dirty, and everything is ... because of this I didn't want to leave.

3.6.2.3 Responsibility for decision-making and self-evacuation policy

I began this chapter by highlighting the different fates of San Miguel Los Lotes and La Reunión in the 3rd June eruption. This relates to a larger issue of the willingness of communities to evacuate from eruptive crisis. In 2019 I found that factors influencing the decision to evacuate was still a central issue among stakeholders at Fuego:

> Official 4:
> They demand of us the answer, "Why did La Reunión leave?" – and it is true, they evacuated in time. "And why not the communities?".

All officials I interviewed spoke of the difficulty of successful evacuation of communities from eruptive crisis of Volcán de Fuego. The same official quoted above spoke of their experience in encouraging evacuation at Los Lotes:

> When we were going through Los Lotes, we were going through warning them, with a siren and everything. I did not see anyone come out. No one, no one. That is, no one expected that ... maybe they imagined that ... somehow, they could have escaped, if [the hazard] had come down the road. But they never imagined that it was going to come out from behind them.

As explained in Section 3.3, the decision to evacuate is co-ordinated between stakeholder groups at Volcán de Fuego. Official responsibility for calling an evacuation at Fuego requires approval either from a community's COCODE or agreed between the community's COCODE and COLRED. In a crisis scenario, self-evacuation policy would have these groups convene and agree to temporarily evacuate their community. Self-evacuation also apparently makes local residents responsible for communicating a community evacuation to, and requesting resources for aid from, CONRED (via UPV). Self-evacuation was being promoted both before and after the 3$^{\text{rd}}$ June 2018 eruption:

2018:

> Interviewer: Yes. And if an eruption like 1974 were to occur again, what would be a 'success' for CONRED?
> Official 2: Success would be that everyone evacuates without us coming. That people call us to say they have begun evacuating, so that we can co-ordinate transport, how to catch buses and reach the shelters. Not that they call us, "Look, what shall we do, come here and get us", less so than that the decision is theirs and they evacuate.
> Interviewer: So that they make the decision – and communicate with you, and you are the ones that give support.
> Official 2: Mm-hm. It is quite difficult.

2019:

> Official 4: Ultimately, I think things have changed. But not everything that we would have liked. What I mean is that possibly there is better risk perception. They know

> what it is, that there is a very serious risk. But . . . but I don't think that the specific ways have been focussed on. For example, in the communities, people wait and see, in any situation in which it is worth evacuating, we have to come and remove them. Everyone. We have to send trucks, we have to send vehicles, transportation. Just like what happened on November 16. People did not leave on their own. ... Eh ... a better example is, "My house is catching fire. I don't expect firefighters to come to take me out. I'll leave, I ...". That is, the first response comes – from the individual level, family level, right, and as a community, it is important. But I understand that it is also difficult.

While officials in 2019 stated that locals have better risk perception, this belief was not fully borne out by my interviews with local people. It is true that many people stated that they were newly aware of what Fuego could do to damage them:

> Resident of San Andres Osuna (East):
> Such a beautiful view, but today we know the ability, the capacity that this volcano has to destroy, don't we?

However, Official 4's statement that "they know ... there is a very serious risk" does not appear accurate for all locals. The resident from Panimaché Dos quoted in Section 3.7.1.1 represented the views of a number of locals who had in 2019 again become accustomed to Fuego's activity. Older western locals also expressed a diffidence towards the scale of the 2018 eruption that contrasts with the quoted statement of Official 4 above. Despite these instances where local and official perspectives differed, coding did reveal a theme where many locals stated that after the 3rd June eruption they would be prepared to evacuate when the situation demanded it:

> Resident of Panimaché Uno (West):
> We saw how [Los Lotes] was left. Well, we are afraid, having seen everything that happened and waiting here. Better to leave . . . leave and not wait any more.

In 2019 I found strong consensus opinion among local residents that it was better to leave immediately when Fuego began displaying signs of unrest rather than waiting for further increase in activity. This consensus was particularly strong in Panimaché Uno, where nine of the 11 people I interviewed stated this in some form. I suggest this is related to the strong relationship between locals and observers in OVFGO1 (see Section 3.6.2.1). Among residents, consensus opinion that it was better to leave immediately than wait was at least partly driven by memories of the 2018 eruption, when waiting became fatal. However, while locals outside of Panimaché Uno also expressed desire to evacuate promptly, this was consistently tied to concerns about risks involved in evacuation. As stated in Section 3.6.2.2, risks that locals at Fuego voiced included leaving belongings and houses unattended (and vulnerable to looting), worries about livestock welfare, and concerns about evacuation shelter conditions or even whether such shelters existed. A particular phrase, “a donde ir” (“where to go”) was recorded in nine separate interviews with locals. The phrase was employed to express the uncertainty that many people felt when considering where to evacuate.

I was fortunate to be able to directly interview staff at La Reunión golf resort. This gave me direct insight into factors that affected the resort’s decision to evacuate in June 2018. From interviews with La Reunión staff and INSIVUMEH/CONRED staff who had worked with them, it transpired that La Reunión had implemented a culture of preventative self-evacuation in which guests and staff evacuated when an explosive paroxysmal eruption of Fuego developed. It appeared that the crucial threshold for self-evacuation was the descent of pyroclastic flows below a certain height in visible barrancas (confirmed in Tobar, 2018 [Tobar, 2018b]). This threshold was not decided by La Reunión staff but by CONRED, who had regular communication with La Reunión management. La Reunión had successfully evacuated several times before June 2018, most notably in the paroxysmal eruption of 31st January – 1st February 2018:

> La Reunión staff 1 (East):
> But that one of February 2018, the first of February I think it was, it scared me a lot when I left the office here and I jumped to see the volcano, and I saw that this cloud, as if it had come above us – then it scared me. But then nothing happened, right? It was only fear!
> Interviewer: A-ha, yes. So you stayed here?
> Staff: No. We evacuated, that time we evacuated … and then on the next day we returned.
> Interviewer: Ah. And in previous years when there were eruptions, … was there a warning to evacuate or not?
> Staff: Yes, they informed us. Yes. They always warned us that we had to evacuate.

From interviews in 2019, I divined several factors that have facilitated a culture of preventative evacuation at La Reunión. For instance, its position as a private resort allows management to force guests’ departure; it enjoys good communication with both INSIVUMEH and CONRED; and resources such as 4x4 vehicles allow rapid escape. With all these advantages, staff argued that evacuation was still not simple:

> La Reunión staff 1 (East):
> What is complicated is that not everyone leaves. Some leave immediately, others we have to insist to them that they leave … they didn’t leave, because always, “Why should we leave if nothing is going to happen”, right?

These findings and their implications are discussed in Section 3.7.2.3.

3.7 Discussion

This section considers results in Section 3.6 in relation to previous literature (see Section 3.4 and with respect to the current self-evacuation policy at Volcán de Fuego. Findings on direct previous experience of eruptive activity among locals, trust and communication between stakeholders, and resources and knowledge are interpreted with an aim to evaluate the potential success of future volcanic risk mitigation efforts at Fuego. While Section 3.6 provides new insight into the experiences of local people who have lived through eruptions of Fuego and the aftermath, this discussion section reveals that volcanic risk at Fuego is highly complex, influenced by multiple socio-economic factors, and sensitive to both changes in physical hazard and to the effects of lived experience, memory, and trust between communities.

3.7.1 Discussion: direct experience of previous eruptive activity

3.7.1.1 Discussion: differences in focus

In Section 3.6.1.1 I presented evidence for differences in observations of Fuego's activity between local residents and satellite (Figure 3.7). Observations by officials closely matched satellite data. What causes these differences? One reason is that officials have information that is unavailable to locals. INSIVUMEH's geophysical monitoring network detects changes in seismic activity at Fuego. These can be correlated with other sources of information to which INSIVUMEH has access, like satellite imagery such as NASA's MODIS and LandSat platforms. While INSIVUMEH and CONRED staff's experiences of recent activity at Fuego correlates with satellite observations, this is likely to be because of coincidence with visual observations of Fuego's summit eruptive activity from OVFGO1 [Lyons et al., 2007, Naismith et al., 2019a]. Visual observations from OVFGO1 (Figure 3.5) generally match satellite data because thermal anomalies detectable by satellite are also visually distinctive (e.g., incandescent fire fountaining). INSIVUMEH combine visual observations with other monitoring tools because frequent cloud cover frustrates observations of Fuego from surrounding communities. The difference in experiences between locals and officials is partly accounted for by the fewer information sources that locals can access to observe changes in Fuego's behaviour.

A second reason for the difference in local and official perspectives could be the 'normalization bias' encountered in other literature (e.g., Haynes et al. [2008]). Normalization bias may incline locals to expect only the experienced, so that they are insensitive to changing risks; this has previously been documented at Fuego: "because they are so aware, they are almost unaware" (pg. 45, Graves (2007) [Graves, 2007]). Findings from interviews with local people (Section 3.6.1.1) suggest that in 2019 local people were accustomed to Fuego's eruptive phenomena. Excepting the extraordinary size of eruptions such as September 2012, relative changes in Fuego's activity do not register with locals. In contrast, INSIVUMEH staff and CONRED staff face the volcano rather than use it as their backdrop. Their point of observation is different.

However, it is unfair to represent local residents as "unaware". Although there is evidence that locals do normalize Fuego's activity, this only partly resolves the difference between locals' and authorities' experiences of recent eruptive activity. Quotations from local people in Section 3.6.1.2 are rich descriptions of volcanic activity that show how vividly they remember previous eruptions. I suggest a different explanation than normalization for this difference: while any paroxysm since 1999 could have evolved into a larger event, few did, and therefore did not require communities to take responsive action. This response is the critical factor which preserves an eruption in local memory at Fuego. It is notable that among the isolated events that locals remember (e.g., September 2012, June 2018), all were associated with disruption of daily community life. This explanation is substantiated by Figure 3.7, showing both local and satellite observations of eruptive activity at Fuego over the last two decades. Each orange arrow represents an eruption that caused widespread evacuations of local communities (pg. 74, [Escobar Wolf, 2013]). Those are the same eruptions that locals consistently described when we asked them about direct previous experience of eruptive activity.

Figure 3.7 lays out the great difference in local and scientific foci on activity of Fuego. Crucial is that both views are partial: years of eruptive activity are not acknowledged by locals, while several eruptions that locals consider significant barely register in satellite data. For example, the eruption of 13th September 2012 provoked the evacuation of thousands of people but produced a peak thermal radiance of 1612.27 MW, smaller than many events occurring since onset of the new eruptive regime in 2015 [Naismith et al., 2019a]. Figure 3.7 does not aim to undermine the utility of scientific observations for understanding eruptive activity. Instead, both sets of observations are valid and need to be recognized and understood in terms of what matters to different stakeholder groups around Fuego. Recognizing the difference between locals' and scientists' views is critical for effective future risk mitigation at Fuego, if these groups wish to collaborate to protect life and assets from eruptive activity. Throughout volcanic risk literature there is evidence that shared views of risk between stakeholders contributes to more effective risk mitigation procedures, for instance at Volcán Tungurahua in Ecuador [Armijos et al., 2017], at Sinabung and Kelud volcanoes in Indonesia [Andreastuti et al., 2019], and at Tristan de Cunha [Hicks et al., 2014].

This difference in views should be *recognized* but not necessarily *resolved*. Certainly, local residents should not have to adapt in order to resolve the difference. The view of some scientists that local knowledge of volcanic risk as insufficient (e.g., Donovan et al. [2014]) does not acknowledge that different points of view can co-exist and be valid [Naismith et al., 2019b]. As Dove (pg. 336, 2008) states: "authority views of risk are themselves inevitably socially constructed and thus contingent in value and efficacy" [Dove, 2008]. Different views of volcanic risk that stem from different focuses on activity can explain conflicting responses to past eruptive crises at Fuego, and if unresolved these conflicts may be repeated in future. For example, during the November 2018 paroxysm, despite CONRED issuing a red alert and sending vehicles to aid evacuation, many locals refused to leave their homes (RT, 2018) [Tobar, 2018a] or to evacuate by boarding vehicles sent by the Guatemalan army (W. Suarez, pers. comm.). In this case, the eruption was viewed as sufficient risk to evacuate by authorities but not by locals. Accordingly, authorities considered that locals were underestimating risk, and conflict arose as the groups differed in their response (or lack of) to the perceived risk [Tobar, 2018a]. This difference in response could be explained if locals believed that evacuation represented a threat to their livelihood or property, or that it would entail further hardship. Another explanation is that authorities were more willing to call an evacuation following their recent experience of June 2018, remembering the human lives lost and widespread media condemnation of CONRED. This explanation speaks to the Dove quotation above. An inverse difference in views of risk has also recently occurred at Fuego, when on 6th June 2018 residents of La Reina in Escuintla observed explosions from the volcano that they interpreted as the beginning of a sequel to 3rd June. This interpretation caused the residents to evacuate and request help from authorities that was not given. The official who shared this information stated: "in the days following [3rd June] ... people wanted to evacuate for any reason." On this occasion, locals recognized a risk from Fuego that authorities did not acknowledge. Locals then desired a reaction that the authorities did not feel responsible for. On both occasions, differences in opinion between stakeholders on whether the level of volcanic risk had exceeded other risks and therefore required action (i.e., the level of volcanic risk people were willing to live with [Few et al., 2017]) caused different responses and resulted in conflict. Acknowledging multiple points of view would avoid such conflicts in the event of future eruptive crisis at Fuego.

3.7.1.2 Discussion: significance of previous large (VEI 2+) eruptions

In Section 3.6.1.2, I reported findings on local experiences of eruptions in 1966, 1974, and 2018. Older locals in western communities describe the long legacy of 1966 and 1974 eruptions on agriculture. They described the 2018 eruption as lesser. In contrast, people in eastern communities described the 2018 eruption as larger than any they or their predecessors had experienced. Some of this disparity between experiences in west and east communities is due to fewer older interviewees in the east. However, the disparity seems genuine. Locals in Ceilán shared parents' stories of an acute event without long-lasting impacts. Differences in impacts are clear in Figure 3.10 and Table 3.6 (compare "three inches of sand" that fell in Ceilán with "two metres of sand" in Panimaché Dos). Given that communities around Fuego are separated by only a few kilometres, Figure 3.10 illustrates that previous direct experiences of volcanic activity can vary dramatically between even nearby communities. This difference matters in influencing the decision to evacuate

[Wachinger et al., 2013]. In 2019, I also found that older western locals frequently compared 1966/1974 with 2018 in terms of severity (Section 3.6.1.2). That older locals experienced the 2018 eruption as relatively minor is key in evaluating volcanic risk at Fuego because of how these locals interpret the risk of an eruption, and subsequently their vulnerability and response. Judging from their failure to evacuate in 2018, I would interpret that locals would not evacuate from a future eruption until it is large enough to provoke a response similar to 1974. As discussed later in this chapter, this has problematic implications.

The 3rd June 2018 eruption formed a consistent thread in local residents' direct experiences of eruptive activity. In 2019, local residents described themselves as highly aware of the risk that Fuego presents. This is consistent with previous studies [Aleyda Xiomara León Ramírez Carné, 2012, Escobar Wolf, 2013]. However, this is also incongruous because although locals in previous studies stated they were risk-aware, in 2019 local people retroactively judged their previous risk awareness to have been lower. The incongruity can be resolved if before 2018 residents were aware of risk from Fuego, but did not imagine the extent of damage it could inflict. If local residents' volcanic risk awareness was lower prior to 3rd June 2018, this is more consistent with Graves' (2007) observations of normalization [Graves, 2007]. The resident from Panimaché Dos quoted in 3.6.1.1 suggests that any heightened risk awareness after June 2018 may be transient. The June 2018 eruption disrupted locals' ability to normalize the threat of Fuego - but the duration of this disruption is uncertain.

The experience that locals previously had low levels of risk awareness, and that the eruption of 3rd June 2018 had significantly increased their risk awareness, was shared by both INSIVUMEH and CONRED staff. Juxtaposition of responses in 2018 and 2019 to the question "are local people aware of the risk associated with Fuego?" is striking:

2018:

> Official 2: It is difficult for us because people don't know the risk that they are exposed to. They are already used to it, and they won't leave their belongings.
> Interviewer: What is the level of understanding of risk? Maybe if pyroclastic flows descend, are the people conscious of what they are, of what risks they carry?
> Official 2: No.

2019:

> Official 3:
> They already know what a volcano is, and where they live. What the risk is.

The belief that prior to 3rd June 2018 local people were unaware of the risk that Fuego presents appears to be shared by locals and INSIVUMEH and CONRED staff, as is the belief that risk awareness has increased since the eruption. Previous studies at Fuego provide a contradictory response to this belief: on one hand, prior to 2018 local people reported high awareness of Fuego as a threat; on the other, the full destructive potential of the volcano does not appear to have been realized [Aleyda Xiomara León Ramírez Carné, 2012, Escobar Wolf, 2013]. The official interviewed in 2019 and quoted above stated that the increased risk awareness around Fuego after June 2018 was important to reduce local peoples' vulnerability to the volcano, as in the event of a future large eruption these people would now know what Fuego was capable of, and such knowledge would encourage them to act in order to reduce their risk. This conclusion is questionable. It is true that experience of similar-magnitude eruptive events is an important tool for locals coping with persistent volcanic activity, and for making informed decisions regarding livelihood in the face of such activity [Few et al., 2017]. However, the older resident interviewed in Morelia in Section 3.6.1.2 illustrates that memories of a previous severe eruptive crisis may in fact discourage action to reduce risk, as increased risk awareness combined with survivor bias may reassure the individual that a subsequent eruption is less severe, and the risk lower. This agrees with the observation by Wachinger et al. [2013] that the severity of previous direct experience of hazard in determining future response [Wachinger et al., 2013]. Furthermore, the widespread local resistance to army-led evacuations during the eruption of November 2018 contradicts this official's conclusions, suggesting either that local risk awareness has not increased, or that risk awareness has increased, but that awareness is not a principal factor influencing local peoples' decision to evacuate. The fact that these evacuations occurred six months after 3rd June, when memories of the eruption were still vivid, indicates that the latter conclusion is more likely. This conclusion is also supported by previous literature [Johnston et al., 1999] which finds that previous direct experience of volcanic hazard increases the *intention* to evacuate from future crisis, but not necessarily the likelihood of acting on this intention.

There is relatively little existing literature that reports assessment of tephra size by local people as a method of evaluating eruptive severity. However, local residents' descriptions of eruptive activity have been documented at Volcán Tungurahua, and the observations interpreted in terms of different eruptive processes [Armijos et al., 2017]. Section 3.6.1.2 shows a similar phenomenon occurs at Volcán de Fuego, where residents use qualitative assessment of tephra size as a method of evaluating eruptive severity. Furthermore, they use this assessment as a factor influencing their decision to evacuate. This speaks of a remarkable awareness of hazard among locals: their identification of changes in tephra fallout is a kind of "qualitative isopach", and is a clever form of monitoring. Furthermore, their association of this change with different eruptive severities indicates some understanding that fall of larger tephra is associated with a more energetic eruption producing a strong eruptive plume capable of more widespread tephra dispersal and representing greater hazard. Despite this impressive awareness, the use of tephra size as a principal parameter to judge eruptive severity has potentially dangerous implications. Firstly, judging an eruption to be severe when *arena* starts to fall, and then making the decision to evacuate, may already be too late. Secondly, the distinction does not acknowledge other hazards independent of this parameter, such as lahar or pyroclastic flow production (hazards that have both been observed frequently at Fuego within the last five years (see Section 3.6.1.3)). During my fieldwork in 2019, people who reported distinguishing between *arena* and *ceniza* in their judgements of eruptive severity were located in Panimaché Uno, Los Yucales, and Ceilán (Figures 3.5 and 3.10). These communities all have evacuation routes that cross major barrancas which could be cut off by lahars. Panimaché Uno also lies close to Barranca Taniluyá, which is a principal route for pyroclastic flow descent. As such, using only *arena*/*ceniza* to determine eruptive severity, and response to eruption, may provide an incomplete assessment of hazard. Again, recognizing these implications is not solely the responsibility of local people, and should depend also on better information and its effective communication from INSIVUMEH and CONRED to locals.

3.7.1.3 Discussion: Local experiences of specific volcanic hazards

Section 3.6.1.3 presented findings from 2019 that local residents lacked a specific word to describe pyroclastic flows, and that the word "lava" was used for a variety of other volcanic hazards. What are the implications of this? As shown by Armijos et al. [2017], a shared vocabulary for volcanic hazards between stakeholder groups may create a concordant set of thresholds for preparedness for volcanic activity . Conversely, absence of shared vocabulary may impede the possibility for agreed boundaries for action between these groups, complicating decision-making in the case of future eruptive crisis when tensions are already high. There is some evidence that specific thresholds for mitigatory action exist within CONRED and INSIVUMEH. For instance, during the February 2018 paroxysm, one official stated that a call for evacuation was issued once pyroclastic flows had descended beyond a certain distance in Barranca Las Lajas. While this threshold resulted in a successful evacuation, the necessity for such thresholds to be understood and implemented by all stakeholder groups is clear given CONRED's current self-evacuation policy that requires the initial decision to evacuate to be taken by local people. For self-evacuation to be successful, INSIVUMEH and CONRED must work together with communities to develop these thresholds. In 2019 I witnessed semi-regular community visits by CONRED to share videos and demonstrations of pyroclastic flows in order to strengthen knowledge and build capacity in local communities. These visits included extensive dialogue between locals and officials that included discussion of different terminology and language. At Volcán Tungurahua, similar efforts are recognized by local people as highly meaningful, providing them with practical knowledge of hazard but also symbolic of their empowerment through learning and owning their decisions [Few et al., 2017]. In my research at Fuego in 2019, discovering an absence of shared thresholds of tolerable risk and common vocabulary of volcanic hazards between locals and authorities indicates that CONRED's efforts to engage with local residents via COLREDs and COCODEs will continue to be necessary for some time. Developing common risk thresholds and hazard vocabulary, and advancing effective emergency risk communication strategies, should be led by

CONRED, given their greater mobility and access to resources than most local peoples'. It should not be assumed that local peoples' recent direct experience of pyroclastic flows is sufficient hazard education.

3.7.2 Discussion: factors affecting evacuation

3.7.2.1 Discussion: trust between stakeholder groups

Evacuation is a powerful tool when seeking to protect life during a volcanic eruption. However, it is complicated and often costly, thus often invoked only in crisis. The different fates of guests and employees of La Reunión and of residents of San Miguel Los Lotes on 3rd June 2018 has been heavily scrutinized, often with the perception that wealth, and consequent access to resources and information, was the author of their destinies. This is debatable because the policy of preventative evacuation that protected life at La Reunión on 3rd June also has precedence among rural communities with many fewer resources. Sangre de Cristo, for instance, has developed a practice of preventative evacuation during eruptive crisis since the paroxysm of 7th August 2007, similar to the self-evacuations at Tungurahua reported in Armijos et al. [2017]. The ability to evacuate or not must therefore be more sophisticated than simply possession of wealth and resources, just as how vulnerability is often correlated to, but not synonymous with, poverty[Blaikie et al., 2005].

Trust in authorities and confidence in different stakeholder groups is crucial in preventative decision-making during crisis[Wachinger et al., 2013]. In 2019, I found that local trust in authorities around Fuego in 2019 was inconsistent (see Section 3.6.2.1). Western locals had good trust in INSIVUMEH due to the presence of community-based observatories and regular visits from scientists in Guatemala City. A similar dynamic occurs at Tungurahua between locals, *vigías*, and scientists from the capital ([Stone et al., 2014, Few et al., 2017]. These locals acknowledge the important presence of the observatory and INSIVUMEH's role in issuing information and instructions during volcanic crisis. Even more than that, western locals were so trusting that they were willing to outsource decisions on evacuation to INSIVUMEH and the observers of OVFGO1, similar to the "trust and responsibility" cause cited by Wachinger et al. [2013] for the disconnect between risk perception and preparedness. Placing such trust in INSIVUMEH has ambiguous connotations. If locals trust in the protection INSIVUMEH affords them, they may be disincentivized to take personal measures to mitigate risk. On the other hand, this trust is essential in ensuring advice from INSIVUMEH will be considered during a crisis. This advice may decisively change locals' response to volcanic risk, either by the content of the advice itself, or more likely because the high levels of confidence in Fuego's observers automatically renders the advice important, as seen with the *vigías* of Tungurahua [Stone et al., 2014]. However, this trust in INSIVUMEH in western communities is complicated by the fact that INSIVUMEH do not have an official mandate to call an evacuation. As such, if INSIVUMEH advises local people to evacuate due to eruptive activity of Fuego, it is not in an official context. This situation occurred in September 2012, when a widespread evacuation of communities was led by the observers of OFVGO1. Unofficially, several people in 2019 told me that this event was the impetus for CONRED's current policy of self-evacuation. However, it cannot be assumed that in future eruptive crises at Fuego, other communities can carry out such an evacuation. For example, no communities other than Panimaché Uno have trained observers already resident. Indeed, the reliance on INSIVUMEH and observers for an informal call to evacuate may lead to a conflict between locals' and CONRED's judgements of risk and subsequent response, as discussed in Section 3.7.1.1. In addition, the lack of confidence in CONRED displayed by some western locals may dissuade them from complying with CONRED's advice during future eruptive crises. These are some of the many conditions that complicate the relationship and trust between authorities and residents of western communities, and more research is required to understand the situation better. However, findings indicate that in the specific case of Panimaché Uno, an acknowledgement of different views and a closer relationship between residents and authorities has had a positive influence on local residents' willingness to evacuate.

Trust in authorities among residents of eastern communities was less clear than in the west. From interviews with local residents who are voluntary COLRED members, I understood that these residents considered that their COLRED as a source of information and trust in the community (similar to INSIVUMEH's observers at OVFGO1 in Panimaché Uno). However, while the trust between western locals and observers was ratified by locals' words, it was more difficult to confirm the extent of trust between eastern locals and COLRED members. It is not clear whether the transfer of responsibility from CONRED to COLREDes (discussed in detail in Section 3.7.2.3) is supported by a lessening in eastern locals' belief that CONRED are responsible for their well-being during crisis. Some members of COLREDes themselves expressed a lack of support from authorities, as expressed by the resident of Los Yucales in 3.6.2.1. There are some parallels to be drawn between COLREDes and the vigía network at Tungurahua. This latter network has flourished in part because volunteers feel they are playing a critical role in providing early warning of volcanic activity and contributing to risk mitigation [Stone et al., 2014]. Contrary to the "trust and responsibility" clause cited by Wachinger et al. [2013] in the previous paragraph, a lack of trust in authorities has multiple effects on local peoples' perspective and behaviour, including an increased tendency to underestimate risk and a reduction in willingness to take preparatory actions against risk from natural hazards [Wachinger et al., 2013]. Therefore, a positive approach to improving volcanic risk mitigation at Fuego would be to promote support of existing COLREDes in eastern communities at Fuego: in the absence of a permanent observatory, a voluntary network may be the best line of communication between locals and authorities. In 2019 I found interesting dynamics in being a COLRED radio operator: on the one hand, it was an important source of pride, but on the other, it could inspire envy 3.6.2.1. In the comparable *vigía* communication network at Tungurahua, a radio is used as a shared resource that provides an important informal communication pathway [Stone et al., 2014]. A practical way to support

COLREDes could be to maintain the radio network with good batteries, ongoing training, and encouraging commitment in participating in reports.

3.7.2.2 Discussion: "Push" and "pull" factors

Socio-economic factors dominate over hazard adjustment in driving decision-making in areas of high volcanic risk [Gaillard, 2008]. Analysis of volcanic events with multiple fatalities in 1986 – 2015 found that 63% of the 1,282 fatalities occurred more than one week after the recognized eruption onset. These fatalities were not associated with insufficient warning time, but instead result from a complex tapestry of factors that either encourage leaving a safe area ("push" factors), or support a return to, or perseverance in, a high-risk zone ("pull" factors) [Barclay et al., 2019] (see Figure 3.3). Case studies at Tungurahua and at Soufrière Hills Volcano in Montserrat highlight asset protection and escape from poor living conditions among those push and pull factors. The same is true at Fuego, as seen in Section 3.6.2.2. Poor shelter conditions have been citepd as both affecting community vulnerability [Lane et al., 2003] and acting as a "push" factor encouraging early return to a zone of high-risk [Barclay et al., 2019], while on the other hand improvements in shelter conditions have been correlated with increased cooperation of locals with repeated evacuations [Armijos et al., 2017]. Apart from a lack of hygiene and overcrowding, the major problems associated with evacuation shelters at Fuego were a lack of food and water and a requirement to bring identity documents and money. If shelter conditions at Fuego are not improved, this may have a significant impact on the success of future evacuations.

3.7.2.3 Discussion: responsibility for decision-making and self-evacuation policy

Section 3.7.2.1 suggested that supporting COLREDes is a positive method of building trust between locals and officials. Supporting COLREDes is also important for the success of the self-evacuation policy at Fuego in future eruptive crises. Set-up of a community COLRED is not trivial. UPV is responsible for initial set-up of a COLRED and training its members (see Section 3.3. However, once founded, a COLRED is supposed to act as a separate entity. Members of a community COLRED are supposed to act as a source of information for the community and advise the COCODE on whether to evacuate during volcanic crisis. Based on this structure of responsibilities and the quotations from officials in Section 3.6.2.3, the presence of COLREDes appears to be an attempt to transfer more responsibility for volcanic risk preparedness to local people by CONRED. However, it is uncertain whether a newly-founded COLRED and its members have sufficient knowledge and training to perform equivalent work to INSIVUMEH in advising a COCODE in times of crisis. While Section 3.6.1.3 illustrates that locals have good knowledge of Fuego's eruptive hazards drawn from direct experience, this does not translate to a clear ability to distinguish when such hazards are at a critical level to leave. Furthermore, although I interpret the creation of COLREDes as a transfer of responsibility for decision-making from CONRED to local residents, it is unclear whether residents accept this responsibility. In fact, there is no clear evidence for a lessening in locals' belief that CONRED are responsible for decision-making and initial response during eruptive crisis. The differences between local and authority views of responsibility for decision-making, and implications for success of self-evacuation policy, are discussed in more depth below.

The self-evacuation policy contains assumptions about local knowledge, resources, and priorities that conflict with this chapter's findings. Assumptions of knowledge are implicit in quotations by officials in 2018 and 2019 (see Section 3.6.2.3 and end of this section). Official 1, quoted at the end of this section, considers that recent direct experience of eruptive activity has increased local residents' risk awareness (supported by literature, e.g., Johnston et al. [1999]), but also that this awareness will motivate future willingness to evacuate. However, Section 3.6.1.1 showed that only nine months after the 3rd June 2018 eruption, many local people appear again to normalize its behaviour. This suggests that in future eruptions local residents will not have the knowledge to distinguish normal eruptive activity from an eruptive crisis that requires them to evacuate. The official quoted in 2018 references local peoples' uncertainty in the face of volcanic activity ("What shall we do?") and presents this as an undesirable situation illustrating failure of the self-evacuation policy. This may be true, but it does not follow that the failure is due to local uncertainty. One must ask why local people lack knowledge of Fuego's activity, and who is responsible for providing such knowledge. Moreover, one may ask why a lack of local knowledge persists at Fuego. Escobar-Wolf (2013) showed that many local people (66% of respondents in 2010, 101 people) considered themselves insufficiently informed of Fuego, agreeing that "you don't know when the volcano will become dangerous, and you need someone else with more knowledge to tell you when you should evacuate". Aside from a distinction between *arena* and *ceniza*, local people in 2019 were similarly uncertain, despite their recent experiences of June and November 2018. For example, the Ceilán resident who described pyroclastic flows in Section 3.6.1.3 was a member of the community COLRED, but had never seen pyroclastic flows before 3rd June 2018. This resident may not feel confident to advise others in the community about appropriate action to take – which for authorities would be evacuation. While knowledge gained by direct experience of natural hazards is important, combining such knowledge with training and access to scientific information is vital to developing local ability to cope with persistent eruptive activity and facility in decision-making regarding evacuation [Mei et al., 2013, Few et al., 2017].

The self-evacuation policy at Fuego also assumes availability of resources that expedite evacuation. In Section 3.6.2.3, Official 4 gives the example of escaping a house on fire to promote self-reliance – but one *should* wait for the arrival of firefighters, confident that their knowledge of the hazard and resources to quell the flames are greater than those of the person at risk, who holds no official responsibility for dealing with the fire. Similarly, while the efforts of CONRED to improve local knowledge of volcanic hazards and encourage resilience through planning and community co-operation are appropriate, I believe these efforts should be in support of, and not in place of, their own greater capacity and official responsibility. Authors such as Haynes et al.

[2008] have shown that local residents face significant barriers responding to volcanic activity that are deeply connected to the root causes of risk. Better evacuation systems and methods of communication may serve to improve this. However, these improvements should be primarily the responsibility of authorities, who have more resources available than local residents to achieve this.

My interpretations of the self-evacuation policy's assumptions about knowledge and resources are confirmed in Figure 3.11, which illustrates the steps involved in self-evacuation in a CONRED infographic. The translated text is given in Figure 3.12. First, Step 1 assumes that every family can create a Family Response Plan, which requires internet access, literacy (both written and computational), and value judgements that themselves require knowledge. Many local people at Fuego lack some or all of these requirements and would not be able to create such a plan. Steps 2 – 3 of the infographic assumes that locals will (a) be able to access information through resources such as radio; (b) be able to interpret the information given through these sources and incorporate it into their decision-making. However, there have been several major eruptions of Fuego in which communication pathways were damaged, most recently in 3rd June 2018. Furthermore, the lack of a shared vocabulary between locals and authorities (e.g., in the descriptions of pyroclastic flows - see Sections 3.6.1.3 and 3.7.1.3) suggests that locals and authorities do not speak the same language, and therefore a shared understanding of tolerable risk does not exist at Fuego. The importance of developing a shared vocabulary has been shown to be critically important in effective risk mitigation at analogue volcanoes [Armijos et al., 2017]. It appears that a shared understanding of tolerable risk does not exist at Fuego. Moreover, whose responsibility is it that this information is (a) accessible and (b) open to interpretation by locals? It is certainly not that of local people themselves. As of June 2020 neither INSIVUMEH nor CONRED have definitively assumed this responsibility and while this chapter does not assign blame to either institution, I argue that INSIVUMEH and CONRED must agree between themselves who will assume responsibility for this subject in order to acknowledge and address its challenges. Returning to Figure 3.11, Step 4 uses ambiguous language ("begin self-evacuation") that implicitly assumes both a willingness and ability to evacuate. At Fuego the ability to self-evacuate is not supported by evidence: for example, ability to evacuate is greatly facilitated by access to vehicles, but most people do not have access to transport and would have to evacuate on foot. This is slow and dangerous and would be greatly complicated by factors such as an eruption at night or having to carry young children or elderly relatives.

The third assumption of the self-evacuation policy (as examined through Figure 3.11 and the quotations of Section 3.6.2.3 relates to direct experience of volcanic activity. If local residents experience a change in volcanic activity that represents increased volcanic risk, they will then decide to evacuate. This approach is comparable to the hazard-perception approach studied in Section 3.4, where individuals perceive changes in their environments and make adjustments to minimize loss. However, both the more recent research on vulnerability presented in Section 3.4

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3. Reconoce el riesgo o emergencia y prioriza tu vida y la de tu familia.
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FIGURE 3.11. Infographic issued by CONRED promoting self-evacuation. Retrieved from CONRED's official Twitter account @ConredGuatemala.

and findings presented in Section 3.6 suggest that this approach has certain flaws. Local residents describe their direct experiences of previous eruptive activity in a manner that shows that what they see is different from what officials see (Figure 3.7). Differences in how locals and officials see eruptive activity include whether they recognize activity as an eruption or not (Section 3.6.1.1), and whether they compare activity to a previous, larger eruption (Section 3.6.1.3). This chapter describes how personal experience influences such differences; factors such as personal values, cultural beliefs and social dynamics are also likely to shape different interpretations of risk Eiser et al. [2012]. Differences in stakeholder interpretations of risk can be understood through mental models which are explored in Chapter 4.3.4 and 4.7.2. Even if locals and authorities recognize the same eruptive activity, it is uncertain how influential this experience is in locals' decision to evacuate. In 2019, some locals stated that in a future eruptive crisis they would not wait for outside aid to come but would evacuate when they considered volcanic risk "high enough". This initially suggests that self-evacuation is a viable policy. However, when asked to describe a specific situation that would require them to evacuate, locals could not do so (with the exception of *arena*/*ceniza*. Locals' lack of a definite threshold for volcanic risk tolerance has

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3 Recognize the risk or emergency and prioritize your and your family's lives

4 Begin auto-evacuating towards your community safe point and report to your local authority.

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FIGURE 3.12. Above CONRED infographic translated to English.

previously been observed both at Fuego (pages 56 - 57, Leon-Ramirez (2012) [Aleyda Xiomara León Ramírez Carné, 2012]) and at analogous volcanoes like Mt. Merapi [Mei et al., 2013]. At Mt. Merapi, locals who were less familiar with official disaster risk reduction strategies were more reluctant to comply with evacuation orders, and several from under-educated areas were tragically killed in 2010 [Mei et al., 2013]. At Fuego, a further complication regarding direct experience of activity and its influence on self-evacuation occurs with the difference between communities on the east and west flanks that has until now not been acknowledged. In multiple studies of evacuation from natural hazards, the only two significant predictors of preparedness to act were (i) severity of previous direct experience of hazards, and (ii) trust and communication with outside stakeholders [Wachinger et al., 2013, Naismith et al., 1979]. These predictors are also the two most explicit differences between eastern and western communities at Fuego (through, respectively, experiences of 20th-century eruptions and links with INSIVUMEH or CONRED). Therefore, a future eruption of Fuego may have very different outcomes between communities that are only a few kilometres apart, just as in 2018 we witnessed the different fates of San Miguel Los Lotes and La Reunión. By assuming that local residents will recognize eruptive activity at Fuego in the same way as officials do, the self-evacuation policy may have critical implications: if a community's knowledge and preparation are overestimated, they may be expected to organize an evacuation that they cannot achieve. Older residents referenced fall of *arena* as indication to evacuate (Section 3.6.1.2). However, the fall of *arena* would suggest the eruption had already reached a critical stage associated with hazards that may inhibit evacuation (e.g., through descent of pyroclastic flows and/or lahars preventing escape by road). Therefore, I would conclude that in a future eruptive crisis of Fuego, older residents would decide to evacuate only when it is too late to do so.

Other than the three main assumptions implicit in the self-evacuation policy, other factors such as communication may hinder the success of self-evacuation in future eruptive crisis. For example, local residents in 2019 stated they would rely on advice from INSIVUMEH or CONRED, consistent with results from Escobar-Wolf (2013) [Escobar Wolf, 2013]. As seen during many previous eruptions of Fuego, this advice arrives either late or not at all. Advice arriving late may reach communities several hours after eruption onset, when activity is at its peak. One explanation for this delay is that institutional advice is often shared via social media, to which local residents have limited access. This factor could be considered within the earlier discussion of access to resources. Other explanations for communication delays relate to Figure 3.2. Although formal communication pathways dictates that INSIVUMEH and SE-CONRED communicate directly with the public, in practice this does not always happen. Information might be filtered through many institutions before reaching the public: from INSIVUMEH to SE-CONRED, to UPV and through the various levels of CORREDes through to COLREDes, before reaching the public. The direction of arrows is also indicative of the one-way direction of communication from institutions to the public, that has been criticized as ineffective in volcanic hazard communication during crisis [Donovan and Oppenheimer, 2014]. Additional factors to consider in how communication may affect self-evacuation at Fuego include, first, that institution advice is often given in technical jargon that is hard to understand; second, that advice may be distrusted because the institution is not considered a trusted source like friend or family. These factors are supported in literature but exploring them in detail is beyond the scope of this chapter. From these findings I conclude that there are many deterrents to a community successfully organizing its self-evacuation from Fuego.

The self-evacuation policy has merit in avoiding bringing more people into an area of high risk. In many environments threatened by persistent volcanic activity, repeated temporary evacuations can be successful, given conditions such as trust between locals and authorities, good evacuation shelter conditions, and security of domestic resources that encourages co-operative or proactive evacuation by locals [Andreastuti et al., 2019, Armijos et al., 2017, Few et al., 2017]. However, the results of this chapter show that in 2019 these conditions were not in place at Fuego. Trust between locals and authorities is heterogeneous around the volcano, suggesting that in the event of a future eruptive crisis, both knowledge of hazards and a willingness to evacuate may be inconsistent between communities, as seen at Mount Merapi [Donovan et al., 2012b, Mei et al., 2013]. Furthermore, the three assumptions implicit in self-evacuation policy – knowledge, resources, and experience – are not validated by findings presented in this chapter from interviews with local residents. Self-evacuation dictates that in the event of crisis, information and advice will issue from INSIVUMEH and CONRED, but local authorities must make the decision to evacuate themselves. However, a lack of shared vocabulary between locals and authorities (e.g., in the term "pyroclastic flow) suggests that the information INSIVUMEH and/or CONRED share during activity may not be understood in the manner intended. Furthermore, in a future eruption conditions may prevail that prevent local people from resources that give them further information of volcanic activity, similar to what occurred on 3rd June 2018 (e.g., low visibility due to cloud, poor phone signal). The lack of such information may discourage locals from leaving in the spirit of prevention encouraged by self-evacuation. In addition, people in rural communities face significant logistical barriers to evacuating. These include a difficulty in reuniting families in rural communities (men generally work in the field, women at home); a high proportion of young children and the elderly; and poor conditions and a lack of resources in shelters that discourage people from evacuating to these areas of low risk. Finally, it is not certain that factors conflicting with the desire to evacuate (fear of looting, concerns for livestock, poor shelter conditions) have been answered convincingly enough to persuade locals to evacuate without experiencing significant negative impact to their livelihoods when they return. On my last night in Guatemala in 2019, an official expressed some final thoughts on the hopes and challenges that lie ahead:

> Interviewer: And what do you think of … have there been changes since the tragedy in June? If another eruption happens now, what are the things that have changed most?
> Official 1: Well, it's that the people know that they are living in a volcanic area. That they cannot confide in it as before, "Ah, it's having another eruption". Another eruption comes – "Ah, it's only making a noise!". Now, I think that they … they are the best volcanologists now. They can distinguish now between pyroclastic flows, lava flows, everything. Now they know perfectly.
> Interviewer: The lived experience.
> Official 1: Yes. That's it, they know now what can happen and where they mustn't be. Because it was all … well, I'm aware that also CONRED people have been working around the volcano for some time. But the people weren't interested, they didn't go to the meetings, no. But now I think that … it's the opportunity for CONRED to work with the communities. And with us too … raising consciousness in people while they can.

3.8 Conclusions

In recent decades, volcanological research has increasingly recognized the importance of including local knowledge to obtain a holistic understanding of volcanic risk. Meanwhile, research on evacuation from natural hazards shows that trust in authorities and direct previous experience are factors that strongly influence the decision to evacuate. This chapter aimed to contribute to the debates above through an in-depth case study conducted over two years at the active Volcán de Fuego in Guatemala. I explored local residents' direct previous experiences of eruptive activity and factors influencing their willingness to evacuate from an eruption at Fuego through the following research questions:

> *At Fuego, paroxysmal eruptions represent a large risk that may reasonably be managed by repeated temporary evacuation of communities. How does the change at Fuego presented in Chapter Two compare to peoples' experiences of volcanic activity? How important are these experiences in determining peoples' decision to evacuate or not in the new eruptive regime?*

This chapter confirmed findings in previous literature that eruptive activity is experienced differently by different people. At Volcán de Fuego, local residents' experiences of previous eruptive activity differ significantly from authorities' experiences over the same period. The changes in Fuego's eruptive behaviour presented in Chapter 2 do not mirror observations by local residents, although locals do describe an increase in Fuego's activity consistent with its reactivation in 1999. Only the largest paroxysmal eruptions in 2015 – 2018 are remembered by locals as "eruptions", as this concept is strongly linked with the need for community response, usually evacuation. In contrast, authorities' experiences of Fuego's recent activity closely match the changes presented in Chapter 2. As well as differences between locals' and authorities' experiences of Fuego's activity, this chapter presented evidence for significant differences in direct experience of eruptive activity between residents of communities on Fuego's western flanks and residents of communities further east.

In addition to the well-understood factors influencing volcanic risk explored in existing literature, this chapter presents evidence of an interesting and previously unreported difference between Fuego's west and east flanks in terms of (1) individual experience of the eruptions of 1966 and 1974, and (2) trust and communication with INSIVUMEH vs CONRED. This discovery suggests volcanic risk may be even more localized than previously considered, and that that experiences of previous eruptions can influence response to activity decades after the initial event. The discovery of a difference between the west and east flanks of Fuego illustrates the importance of responsibility and choice in responding to eruptive activity. Local people are highly constrained by their responsibilities to their land and livelihoods, they may hold a strong attachment to their home, and the choices that they make are influenced by this. Previous experiences of livelihood devastation in the 20th century appears to have influenced, and continues to influence, the choices of local people on the west flanks of Fuego in a way it has not further east. The different relationships between INSIVUMEH and CONRED with communities on different sides of the volcano provides them with different information and different sources of trust that in turn shape an individual's risk at Fuego. As in analogous environments such as Volcán Tungurahua, volcanic risk is not static but variable with time and location. An individual living in Ceilán and volunteering in its COLRED lives with a completely different risk from that of his elderly isolated aunt whom he visits in Panimaché Uno.

Assessing how local residents experience eruptive activity and trust in authorities allow us to consider (1) how these two factors influence their decision to evacuate from eruptive crisis; and (2) how CONRED's current policy of self-evacuation should be viewed in light of the findings. Differences in how people experience eruptions may impact the success of future evacuation efforts because different people disagree in the threshold of volcanic risk that can be tolerated before a decision to evacuate is made. At other volcanoes, acceptance of both local and official experiences has created effective adaptive volcanic risk mitigation strategies. I believe that at Fuego, local residents' direct experiences of previous activity are an under-used resource; acknowledging these experiences by including them in training and policy may empower locals and encourage their collaboration with INSIVUMEH and CONRED in strengthening existing risk mitigation strategies.

The current policy of self-evacuation encourages community empowerment by transferring the responsibility for the decision to evacuate to local communities. It also has the additional benefit of avoiding bringing more people into a high-risk zone. Nevertheless, this chapter shows that self-evacuation contains implicit assumptions about local residents' knowledge, resources, and experiences. These assumptions were not confirmed by interviews with local residents. Local residents are knowledgeable of Fuego's activity but lack knowledge of specific hazards such as pyroclastic flows to make the decision to evacuate without difficulty. Other factors as lack of resources and security fears further complicate the decision to evacuate.

There are many future directions for volcanic risk research at Fuego. Ideally it would incorporate a longitudinal component to observe how risk, and risk awareness, change with time as we move forwards from the tragedy of 3rd June 2018. Researchers could study the duration of increased risk awareness after an eruptive crisis, and its importance in influencing preventative action among local residents. Alternatively, future research could consider the role that specific stakeholder groups (e.g. COLREDes) play in shaping risk and its mitigation at Fuego. Fuego remains a highly active volcano, and the populations close to its summit continue to increase. If risk mitigation policy fails to recognize the different ways of experiencing eruptive activity, or ignores the social and economic pressures that may disincentivize locals from making the decision to evacuate, it is uncertain whether the rich knowledge of hazards and qualitative assessments of risk that local residents include in their experiences of Fuego's activity may translate into them taking sufficient protective measures to preserve life in the case of a future explosive eruption.

CHAPTER 4

TRANSITIONS

4.1 Abstract

This chapter shares some of Chapter 2's focus on Fuego's accelerating paroxysmal cycle in 2015 – 2018. It analyzes individual events within this cycle to determine patterns in geophysical data that may be used to forecast paroxysm. This analysis also provides a template for timescale of eruption at Fuego, including the effusive-explosive transition that occurs as a paroxysm of Fuego reaches climax. Because Fuego's largest paroxysms generate hazards that threaten lives and livelihoods, this chapter also studies several paroxysms which provoked evacuation in order to derive a template for timescale of response. Eruption and response timescales are compared to explore variability of each and redundancies or shortfalls between. Patterns in geophysical data described in eruption timelines are debated in terms of their relevance to INSIVUMEH's forecasting efforts and to warning messages shared with vulnerable communities around Fuego. In addition, I introduce some analysis of spatial variability of risk by including hazard maps from INSIVUMEH and evacuation routes from CONRED. This addition is necessary because of the geographic variability of volcanic hazards explored in Chapter 3, which described how past eruptions of Fuego have unevenly affected different communities around the volcano. The central question I hope to answer with this analysis is whether the current monitoring and risk mitigation network at Fuego provides sufficient warning time of impending activity to mitigate risk to locals.

This chapter finds that eruption and response timescales are comparable at Fuego. The chapter also presents evidence that timeframes of response lag behind eruptive evolution due to long periods of decision-making and warning. These periods are evaluated through the self-evacuation policy and communication network at Fuego and through different stakeholders'

mental models of risk. Chapter findings are relevant to both institutional and local stakeholders at Fuego. For institutional stakeholders, exploring timescales of activity and response can determine if current risk mitigation policies (including self-evacuation) are likely to be successful in future eruptive crises. For local residents, understanding whether and how timescales of response factor in their mental models of risk may suggest practical ways to encourage protective actions such as evacuation. **The key message of this chapter is that the current monitoring and communication infrastructure at Fuego does not allow sufficient time to mitigate risk to local residents. In addition, differences in mental models between stakeholders (and lack of opportunities to compare these differences) has substantial implications for the ongoing vulnerability of local residents to volcanic hazards of Fuego.**

4.2 Introduction

Chapter 1 introduced Volcán de Fuego as an ideal environment to study both eruptive activity and human response. Chapter 2 provided an overview of Fuego's eruptive activity and associated hazards between 2015 and 2018 through satellite imagery and bulletin reports. I presented evidence for a new eruptive regime characterized by frequent paroxysmal eruptions consistently preceded by lava effusion. Chapter 2 also showed that paroxysms at Fuego consistently produce pyroclastic flows. The only preventative action from pyroclastic flows at Fuego is evacuation. Chapter 3 studies human response to Fuego's activity by exploring local residents' experiences of previous eruptions and evacuations. This fuelled discussion of factors affecting the decision to evacuate. Ultimately, it found that the current self-evacuation policy at Fuego contains implicit assumptions about local residents' knowledge, resources, and priorities. The chapter concluded by acknowledging the different ways that stakeholders interpret volcanic risk at Fuego, and cautioned that if risk mitigation strategies fail to recognize these differences, it is uncertain whether such strategies will be effective in protecting lives of local residents in the event of a future explosive eruption.

This chapter builds on the previous two by studying eruptive activity and human response in parallel. These themes are examined through timescales of activity and response for several eruptions since 1999. This investigation aims to answer the question, *What warning time for impending eruptive activity is needed to mitigate risk to local residents?*

Volcanoes are complex systems; eruptions are driven by intricate processes. Forecasting eruptions is a central goal of volcanology [Sparks, 2003] but is currently largely beyond our reach, especially at volcanoes like Fuego where geophysical data of eruptive activity are sparse. Nevertheless, a primary objective of both INSIVUMEH and CONRED is reducing uncertainty associated with eruptive activity that presents the greatest risk to human life. Chapter 2 identified pyroclastic flows as a fast-acting hazard at Fuego, and Chapter 3 recognized evacuation as the only action that prevents loss of life from such hazards. However, other hazards of Fuego act on different timescales and present different threats to local livelihoods. An important question is over what timescales does a paroxysm of Fuego evolve to generate hazards that threaten local communities? That is the subject of Section 4.6.1.

In exploring experience, Chapter 3 implicitly considered timescales of response to eruption: locals spoke of delays in arrival of warning messages, and waiting for the arrival of vehicles in which to evacuate. This chapter follows the work of Chapter 3 by explicitly exploring timescales of response. This appears in Section 4.6.4.

Exploring timelines of eruption and response at Fuego will identify uncertainties involved in each. In addition, this analysis may reveal redundancies or shortfalls in the time afforded to evacuate from eruption by the current monitoring and risk mitigation capacity at Fuego. Implications of these findings will foment discussion of (i) where to focus efforts to strengthen monitoring capacity, to improve anticipation of future eruptive crises; (ii) where to focus efforts to strengthen risk mitigation strategies, to maintain awareness of risk during quiescence.

To augment discussion of the question above, this chapter includes a mental models approach to volcanic risk. This approach describes how different stakeholders interpret risk, and when used at Fuego shows the implications of interpretive differences for success of current risk mitigation policy in future eruptions. This approach allows me to directly deal with the objective stated in this thesis' introduction, that of integrating hazard assessment and risk mitigation for a holistic understanding of a volcano. The analysis highlights a tension in this thesis that is well-known in volcanology: a disparity between physical and social sciences in timescales over which relevant forces operate. This tension provides an opportunity to study the world beyond Fuego and highlight some promising areas of interdisciplinary volcanological research that aim to resolve this temporal disparity between physical and social sciences. These areas are explored in the concluding chapter.

4.3 Background

This section introduces timelines as powerful chronicles of both eruptive activity (as timeseries datasets) and human response (as narrative devices). Timelines effectively illustrate temporal variations in risk during eruption. In addition, they can contain a spatial element to describe how risk varies geographically. The concept of mental models of volcanic risk is introduced and integrated with previous approaches taken in this chapter.

4.3.1 Timeseries as chronicles of eruption and response

The many physical processes and human actions involved in a volcanic eruption make it difficult to clearly describe the event. However, detailed description is essential for understanding what processes and actions contributed to disaster or prevented loss, and what lessons may be learned before the next eruption. Timeseries efficiently tell the story of an eruption in a single figure. In particular, timeseries analysis can narrate how a volcano evolves from effusive to explosive behaviour (e.g., at Stromboli [Ripepe et al., 2005, Delle Donne et al., 2017], Etna [Allard et al., 2006], or Santiaguito [Lamb et al., 2019]). Timeseries analysis of patterns in geophysical data during effusive-explosive transition can elucidate cause(s) of eruption. The value of integrating timeseries from multiple geophysical datasets has been demonstrated on several occasions when these timeseries contributed to timely warnings declared for impending eruptions [Sparks, 2003]. Figure 4.1 illustrates how uniting multiple timeseries datasets can effectively tell the story of an eruption. This figure describes activity at Mt. Etna in January - December 2016. Parallel analyses of SO_2 flux, satellite, and seismic timeseries reveal three distinct periods of activity: first, a pre-eruptive period characterized by low activity; second, an eruptive period including powerful lava fountaining; finally, a post-eruptive phase that included a brief cessation in eruptive activity. These parallel analyses allow tentative identification for thresholds between eruptive regimes [Delle Donne et al., 2019]. In turn, identifying thresholds is essential for identifying corresponding levels of volcanic risk [Fournier d'Albe, 1979].

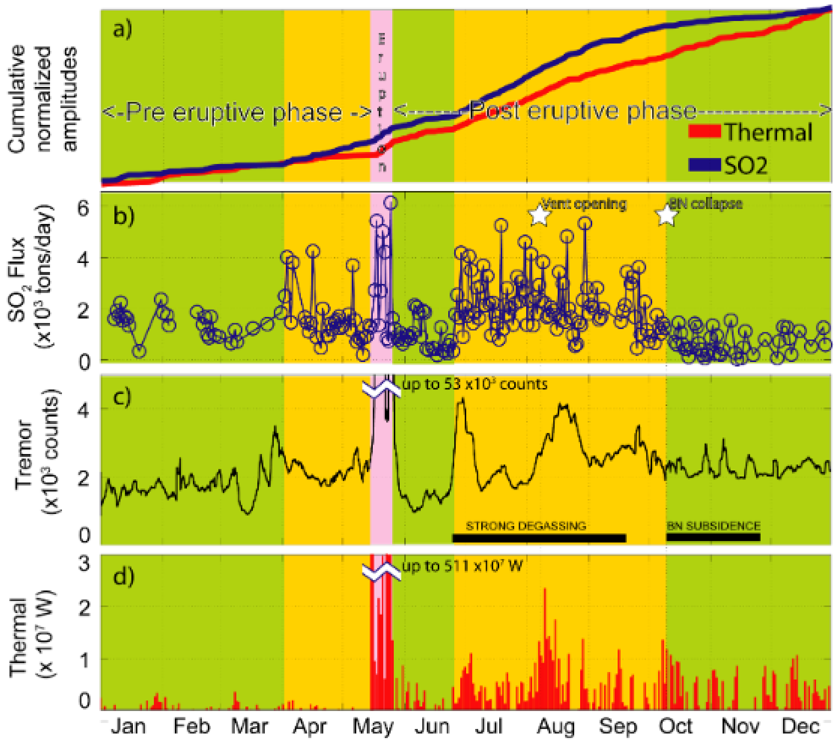


FIGURE 4.1. Timeseries can efficiently tell the story of an eruption in a single figure. This figure uses timeseries datasets to show transitions between (1) pre-eruptive, (2) eruptive, and (3) post-eruptive periods at Mt. Etna in 2016. From Delle Donne et al. [2019].

Understanding the processes that drive transitions between effusive and explosive activity is vital for both forecasting future activity and mitigating associated hazards [Delle Donne et al., 2017]. It is clearly useful for scientists to understand and discuss such processes because monitoring data and underpin assessments and advice at many volcano observatories [Donovan, 2019]. Understanding the underlying process allows for better data interpretation. Given that scientists are often tasked with advising authorities Donovan [2019], and that local people often have to rely on scientists for information to manage volcanic risk [Johnston et al., 1999], scientists' improved understanding of transitional processes at Fuego is also indirectly valuable to local people, authorities, and risk managers. The utility of timeseries for anticipating imminent activity depends on how fast scientists can process and interpret the data. The near-real-time results promised by automatic data capture campaigns such as those illustrated in Figure 4.1 suggest that timeseries show real promise for forecasting future eruptions. A more thorough discussion of timescales involved in forecasting and responding to activity appears in 4.3.2.

Multiparametric timeseries analysis provides a robust way to chronicle eruptive evolution because different geophysical parameters are differently sensitive and show patterns over different timescales. Parameters frequently used to monitor effusive-explosive transitions include thermal values from satellite data, RSAM, seismic event rates, and gas flux. RSAM has be used to distinguish between eruptive styles (e.g., between magmatic and phreatomagmatic eruptions, as described by Endo and Murray [1991]), while satellite timeseries can trace decrease in thermal output as lava effusion ceases with a transition to explosive activity [Ripepe et al., 2002]. Meanwhile, SO_2 fluxes trace smaller changes in activity Edmonds et al. [2003]. This chapter integrates timeseries of parameters with different temporal and spatial resolutions in order to create comprehensive timelines of eruption. These timelines define a range for available response time. Timelines are also evaluated to consider any potential patterns in seismic, satellite, and SO^2 data that may be used for improved forecasting of future eruptive events at Fuego. (Of course, future forecasting will still be subject to uncertainty: Section 4.7.1 discusses uncertainties and forecasting approaches relevant to geophysical timeseries results.)

4.3.2 Paired timelines to understand eruption and response

An eruption of a populated volcano that provokes emergency response is an event involving both space- and time-limited physical hazards and human actions that must be understood in a broader social context. Timelining is recognized as a valuable tool for narrative forms of research [Sheridan et al., 2011, Sword-Daniels et al., 2015]. Narrative research aims to understand how "human actions are related to the social context in which they occur" [Moen, 2006]. Therefore, pairing narratives of eruption and response allows integration of physical and social science that is the ultimate purpose of this thesis.

Comparing narratives of eruption and response can reveal important details about both processes; for instance, whether there are redundancies or shortfalls in warning or response. Such information is crucial to strengthen existing risk mitigation policy. Timelines that explore eruption and response may also include type and intensity of communication during eruption and the nature of evacuation. These timelines can reveal temporal and spatial fluctuations in risk around a volcano and therefore effectively illustrate the dynamic nature of volcanic risk [Jumadi et al., 2020]. Figure 4.2 describes an eruption of Volcán Tungurahua in 2006 and parallel stakeholder community responses. Information included is seismic timeseries, explosion data, observations of ash and pyroclastic flow, and evacuation dynamics. Synthesis of these datasets, as well as comparison with a similarly constructed timeline of an eruption in 2014, allows for sophisticated analysis that reveals how risk changes through time and space around an active volcano [Armijos et al., 2017]. The analysis also highlights aspects of risk particular to Tungurahua, such as the evolution of informal communication networks that interface with formal communication lines to encourage preventative evacuation (compare Official and OVT/Vigía Communications timelines in Figure 4.2) [Armijos et al., 2017]. Paired timelines permit simultaneous assessment of eruptive activity, forecasting efforts, and evacuation decisions, as shown in Syahbana et al. [2019].

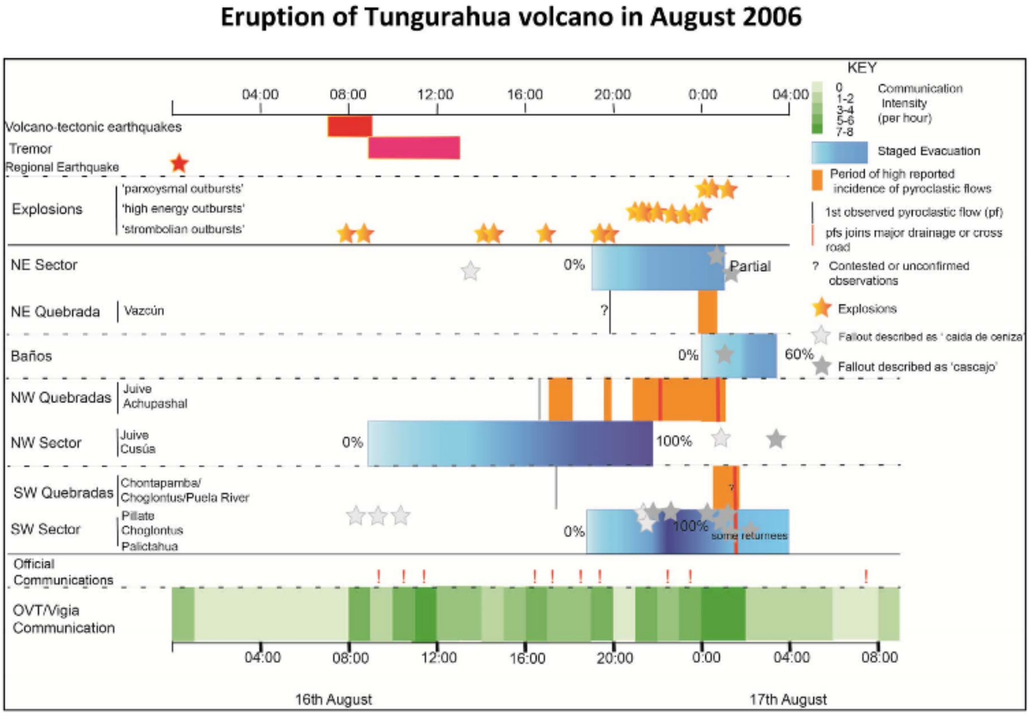


FIGURE 4.2. Timelines tell the story of both eruptive behaviour and response from various stakeholders at many volcanoes analogous to Fuego. This shows the eruption of Volcan Tungurahua, Ecuador, in 2006 and associated response from risk managers and communities. From Armijos et al. [2017].

“Effective volcanic risk management requires that prediction should cover time intervals comparable with the time-scale of human and social responses to them" [Fournier d’Albe, 1979]. Different eruptive events evolve at different rates. While the case studies explored in Mei et al. [2013] and Lechner and Rouleau [2019] use past experience to inform present practice, models allow for evaluation of eruptive scenarios that have not happened yet. Marrero et al. [2013] use models to create several eruptive scenarios to estimate timelines involved in evacuation at Volcán El Chichón, Mexico. Figure 4.3 visualizes the relationship between forecasting and evacuation timelines. The key message of this figure is that evacuation is not a single decision but a series of actions: making the decision to evacuate, disseminating the warning message, preparing for evacuation (or self-evacuation), and the evacuation process itself. Each action is associated with a timescale that may be affected by many factors. Several time intervals inform this chapter’s results and discussion. Warning time (WT) is the time period between when the warning message is announced by officials and when the exposed population are believed to have received and understood it. The available evacuation time (AET) is the period between when the forecast is announced and when the eruptive event takes place, while the mitigation action time (MAT) is the period between when the evacuation decision is made and when evacuation has been successfully completed [Marrero et al., 2013].

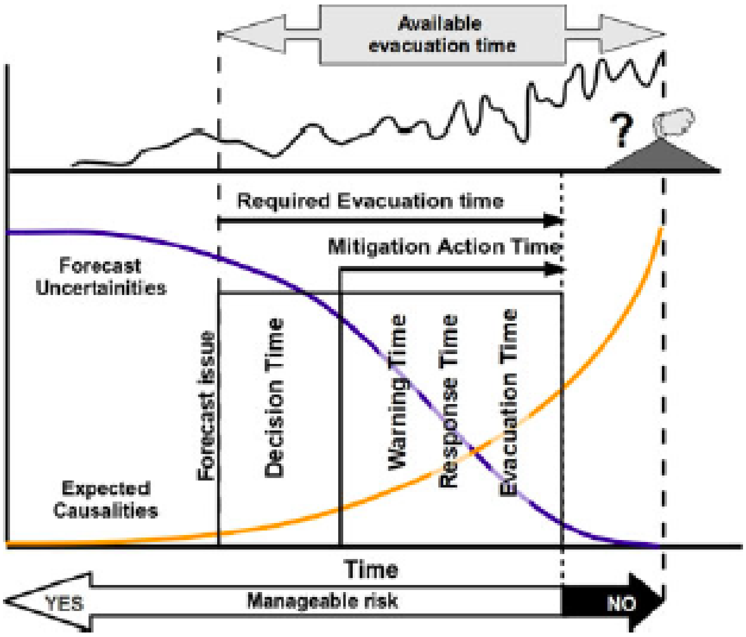


FIGURE 4.3. Relationship between forecasting and timelines for evacuation illustrate whether risk is manageable. From Marrero et al. [2013].

Following the eruption of Fuego on 3^{rd} June 2018, a World Bank workshop outlined objectives for improved volcanic risk management in Guatemala. These included strengthening INSIVUMEH's monitoring capacity and implementing a communication strategy between INSIVUMEH, CONRED, and communities in high-risk zones that acknowledges cultural characteristics of those communities BancoMundial [2018]. If realized, these objectives may help increase AET and MAT through, respectively, decreasing forecasting uncertainty and improving trust in authorities. INSIVUMEH's capacity for monitoring Fuego's activity has increased since 2018, as discussed in Chapter 2.6.4. Fuego fits the scenario discussed in Marrero et al. [2013] where the objective is to reduce the MAT "in places where the population at risk is widely dispersed over terrain of difficult access". In this scenario, constraining the warning time is essential for risk managers and evacuation drills are the solution proposed. BancoMundial [2018] includes evacuation drills as a main objective for CONRED to lead for improved risk management at Fuego.

4.3.3 Spatial variability in volcanic risk

Volcanic risk is dynamic in time *and* space. Studies at many populated volcanoes have shown the large differences between how even nearby communities experience, prepare for, and act in response to eruptive activity (see Figures 4.2 and 4.4). A timeline tells a story of eruption and response; adding geographical information highlights that a single eruption creates many different stories depending on place. Figure 4.4 illustrates this point through mapping local subcultures around Mt. Merapi, Indonesia, in 2007 and 2009. Interviews with, and observations of, local residents revealed how motivation to evacuate changed dramatically within a few kilometres. Mapping previous and potential future actions in volcanic crisis reveals spatial differences in the reason(s) for residents' reluctance to comply with evacuation orders. Chapter 3 began to explore spatial variation in risk at Fuego itself through experiences of previous large eruptions (see Chapter 3.7.1.2). As shown in previous literature (e.g., Wachinger et al. [2013]), prior direct experience of activity (modified by severity) is important in determining future response to a hazardous event. This chapter builds on findings from the previous chapter by considering how proximity to hazardous areas and evacuation routes affect how risk varies spatially at Fuego.

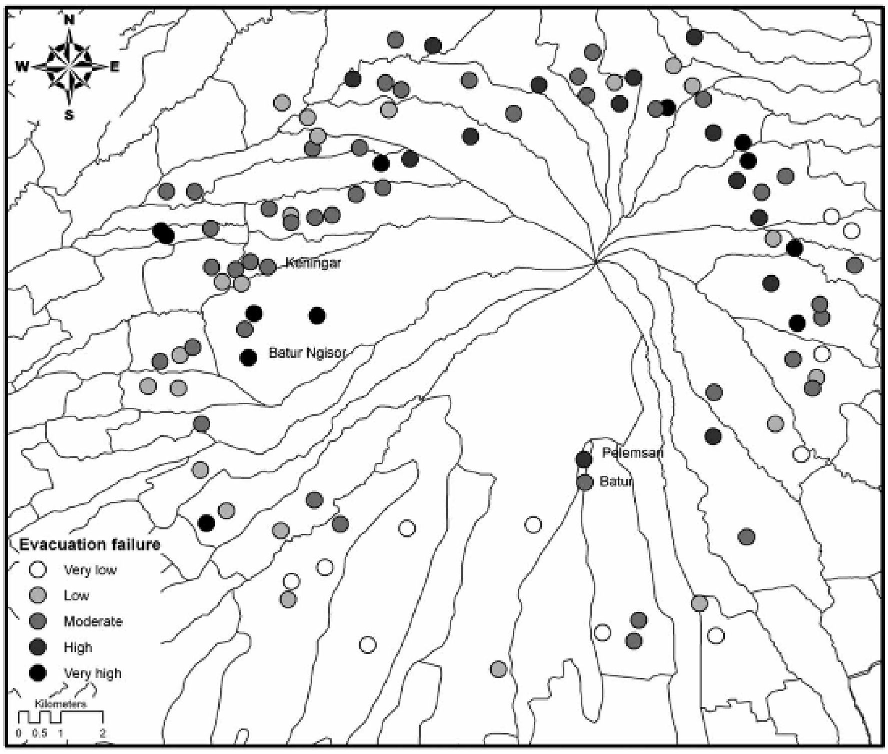


FIGURE 4.4. Spatial variability in exposure to hazard and responses to eruption can vary greatly in even geographically close communities. Here, coloured circles show likelihood of refusal to evacuate among communities on the flanks of Mt. Merapi, Indonesia. Light grey circles represent communities most likely to refuse an order to evacuate. Medium grey circles relate to those that prefer either to await traditional signs before evacuating or to observe the situation for themselves. White circles are areas willing to evacuate under specific conditions; dark grey, those that have never evacuated. From Donovan et al. [2012b].

4.3.4 Mental models

Timelines explore *how* response to eruption unfolds; it is also essential to understand *why*. Mental models describe people's thought processes about how things work in the real world; in risk research, they describe how different stakeholders interpret risk to themselves [Eiser et al., 2012]. While timeline analysis describes how stakeholders have acted in previous eruptive crises, mental models may explain why, and thus how people may act in future events. Figure 4.5 shows a mental model for how residents vulnerable to hurricane risk decide on responsive action, whether evacuation or another (e.g., search for more information). The model includes factors that influence this decision, such as household characteristics of the message recipient, situational motivations and barriers, and external information. Situational barriers to responsive action at Fuego were explored in Chapter 3.7.2.3 and appear in the Protective Action Decision Model (PADM) used to explore response to eruptive crisis at Fuego [Escobar Wolf, 2013] and at Pacaya [Lechner and Rouleau, 2019]. External information, including forecasts and warning messages, is a critical element of a mental model. Previous research advocates for thinking of such information as a system with both informal and formal elements, an approach likely to improve risk communication for both volcanic [Armijos et al., 2017] and other natural hazards (e.g., hurricanes) [Bostrom et al., 2016]. Communicating the efficacy of evacuation to a threatened population increases intention to evacuate, as does prior experience of evacuation; the latter possibly because if an individual has successfully evacuated before, they have proof of their ability to do so in future, and knowledge that this will successfully protect them from the hazard [Morss et al., 2016]. Conversely, uncertainty in the appraisal process complicates the response decision. Different stakeholders understand and communicate uncertainty in diverse ways: monitoring scientists may describe numerical uncertainties involved in forecasting, while public officials consider how uncertainty interacts with protective decision-making [Bostrom et al., 2016]. This includes a cost-benefit analysis of a response such as evacuation: "managing uncertainty in the ... warning system involves trade-offs between the benefits and costs of warning people or taking protective action" Bostrom et al. [2016]. In a volcanic context, message recipients tend to underestimate event likelihood when its uncertainty is communicated in verbal terms, and skew their expectations of event likelihood towards the end of a given time window of occurrence [Doyle et al., 2014]. Exploring differences between stakeholder mental models of information appraisal and decision response is critical for anticipating potential outcomes during future volcanic crises:

> It is ... important to understand how scientists and other authorities impose meaning on, interpret and understand the distribution of the outcome likelihood within these time frames. This meaning is developed within different professional frames of reference and groups with different goals, and any meaning derived from the scientists' mental model maybe inconsistent with a practitioner's mental model and goals (e.g., what may happen vs. do we need to evacuate or not).
>
> [Doyle et al., 2014]

At Fuego, the rapid evolution of paroxysmal eruptions and related hazards (Chapter 2) make it important to study scientists' and officials' mental models for appraisal and response within a short time window. In addition, it is crucial to study local residents' mental models given the responsibility for the decision to evacuate is currently theirs (Chapter 3). Figure 4.5 is a useful mental model for exploring timelines of eruption and response actions in this chapter due to its iterative structure, where a response action can be to wait and seek more information and thus returning to the beginning of the process. As findings in this chapter will show, this is a common scenario for both authorities and local residents at Fuego.

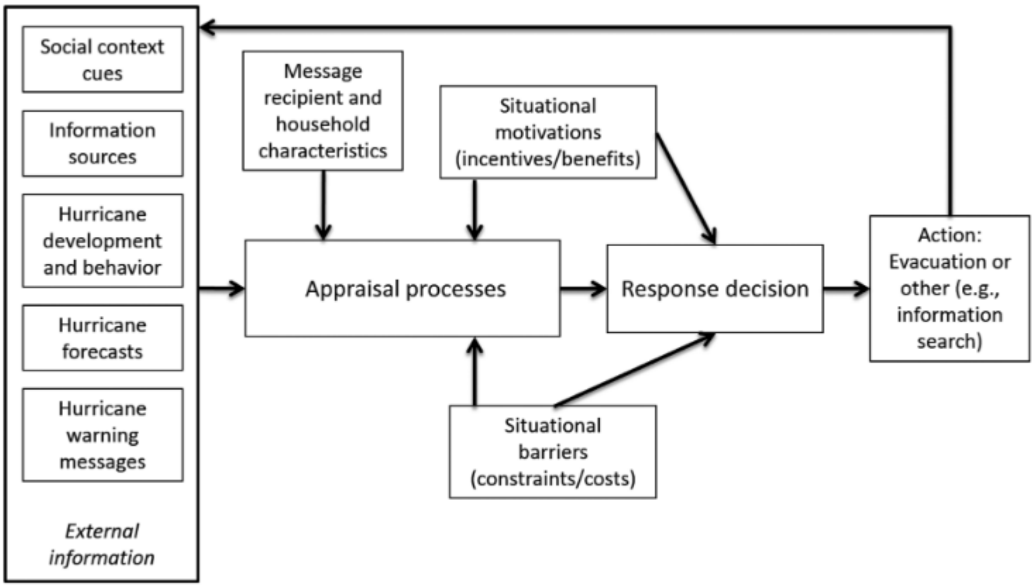


FIGURE 4.5. Mental model for appraisal of information and response to hurricane risk. Model constructed from semi-structured interviews and pilot study to theorize how warning messages and other factors influence evacuation decision-making. From Lazo et al. [2015].

4.3.5 Forensic Investigation of Natural Hazards (FORIN)

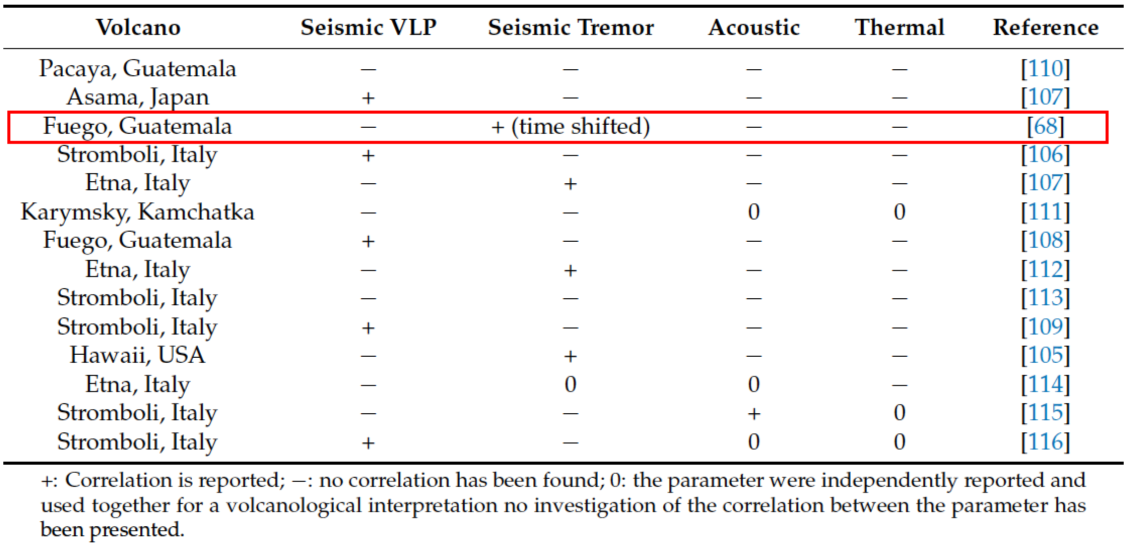
This chapter integrates triggering of natural hazards and stakeholder responses at Fuego that have been explored separately in Chapters 2 and 3. This is a complex task requiring the involvement of approaches and methods from multiple disciplines. This resembles the approach of FORIN (Forensic Investigation of Disasters), which seeks to unite investigations on the root causes of disaster to generate "a new body of knowledge that is more than the sum of its separate and component parts" [Oliver-Smith et al., 2016]. FORIN acknowledges that physical triggering events are an essential condition for disaster; however, disasters involving these events are primarily social processes that unfold over time [Oliver-Smith et al., 2016]. In addition, "The principal conceptual difficulties that must be bridged are the epistemological challenges of identifying research questions that multiple disciplines and stakeholder communities can embrace, and in which different methodologies can pursue relevant information of different qualitative-quantitative natures across time/space/organizational scales." [Oliver-Smith et al., 2016]. This section presents the research question, *What warning time for impending eruptive activity is needed to mitigate risk to local residents?* as one that can be explored through both physical volcanology and social science disciplines and through the experiences of locals, scientists, and risk managers. This section also introduces the tool with which to answer this question: timelines or timeseries, depending on the discipline. Although this chapter studies timelines of specific eruptions at Fuego, it also presents findings of many causal factors of disaster that play out over the longer term than a single, spatio-temporally delimited event. This supports the findings of Chapter 3, which revealed the lasting effects of previous eruptions and evacuation experience. The paired timeline analysis and mental models discussion in this chapter shows that eruptions and response can be understood on multiple timescales: both the shorter timescales of the individual event, but also longer timescales of social processes. The discussion section includes the question of whether these different timescales are acknowledged in hazard assessment and risk mitigation strategies in Guatemala, and implications for future eruptive crises.

4.3.6 Relevant previous work at Fuego

4.3.6.1 Timeseries analysis to constrain eruption timescales

Uniting SO_2 and geophysical timeseries data is an effective way to illustrate changes in eruptive behaviour. Platt et al. [2018] present an excellent synthesis of multiparametric monitoring studies that includes a summary of studies conducted at Fuego (Figure 4.6). The "-" symbol in Figure 4.6 means that correlation between parameters has not been found, and more research is required to determine any interrelationship. Nadeau et al. [2011] found a strong correlation between volcanic tremor and SO_2 flux using equipment deployed in 2009. This study also established a tentative link between SO_2 release and seismic amplitude associated with explosive activity at Fuego. Although Figure 4.6 shows that a correlation between SO_2 and VLP has not been definitively proven at Fuego, there is preliminary evidence for correlation between spikes in SO_2 and impulsive VLP events [Waite et al., 2013] observed in 2008. These VLP events were associated with impulsive, bomb-rich explosions from the summit vent. These explosions were interpreted to be partial sealing then release of ash-free gas from Fuego's summit vent [Waite et al., 2013]. Meanwhile, the relationship between SO_2 flux and seismic amplitude at Fuego observed in 2009 could be interpreted as either ascent and burst of gas slugs or brittle failure of a viscous magma plug in Fuego's upper conduit; symmetry of these results with observations of apparent tilt favours the latter interpretation [Lyons and Waite, 2011]. However, the much higher frequency of small explosions and exhalations of SO_2 compared with explosive SO_2 tied to VLP events suggests that complete sealing of Fuego's conduit is difficult to achieve [Lyons and Waite, 2011]. The "leaky plug" is consistent with perception of Volcán de Fuego as an open-vent system.

A good deal of literature using timeseries data to study Fuego has been conducted at Michigan Technological University (MTU) on eruptive behaviour in 2008 – 2015. Nadeau et al. [2011] found a correlation between RSAM and SO_2 that indicated a relationship between degassing and seismogenic tremor. This correlation was inconsistent, as the authors observed periods where RSAM remained high while SO_2 fluctuated. Periods of correlation between RSAM and SO_2 were



Volcano	Seismic VLP	Seismic Tremor	Acoustic	Thermal	Reference
Pacaya, Guatemala	−	−	−	−	[110]
Asama, Japan	+	−	−	−	[107]
Fuego, Guatemala	−	+ (time shifted)	−	−	[68]
Stromboli, Italy	+	−	−	−	[106]
Etna, Italy	−	+	−	−	[107]
Karymsky, Kamchatka	−	−	0	0	[111]
Fuego, Guatemala	+	−	−	−	[108]
Etna, Italy	−	+	−	−	[112]
Stromboli, Italy	−	−	−	−	[113]
Stromboli, Italy	+	−	−	−	[109]
Hawaii, USA	−	+	−	−	[105]
Etna, Italy	−	0	0	−	[114]
Stromboli, Italy	−	−	+	0	[115]
Stromboli, Italy	+	−	0	0	[116]

+: Correlation is reported; −: no correlation has been found; 0: the parameter were independently reported and used together for a volcanological interpretation no investigation of the correlation between the parameter has been presented.

FIGURE 4.6. Comparison between SO_2 fluxes and geophysical parameters with Fuego highlighted. Adapted from Platt et al. (2018), itself expanded from Burton et al. (2015). Reference 68 is the paper by Nadeau et al. (2011).

quantified through cross-correlation within multiple time windows, showing a maximum correlation of 0.6 with SO_2 trailing seismicity by 32 seconds. The authors interpreted this correlation as the continuous rise of bubbly fluid through a resonant crack creating an impedance contrast large enough to produce sustained tremor. During times where high RSAM was unmatched by SO_2 flux, the authors suggested a second seismicity source that contributed to RSAM and overprinted the gas-sourced signature [Nadeau et al., 2011].

INSIVUMEH frequently use RSAM to trace evolution of paroxysm at Fuego, as shown in Special Bulletins reporting eruption. Castro-Escobar [2017] determined a correlation between RSAM with paroxysmal onset by noting large-scale increases in RSAM that accompanied eight paroxysmal eruptions in January – October 2015. Outwith this correlation, the author found no distinctive parallels between RSAM and other datasets. More recently, Aldeghi et al. [2019] have combined timeseries data from satellites with reports of hazards and eruptive styles to chart evolution of an individual paroxysm on 31st January – 1st February 2018 (Figure 4.7). In this work, detailed satellite imagery captured short-lived events and were compared with images from a longer timeseries to provide context. While the focus of Aldeghi et al. [2019] is to study crater morphological changes through satellite data, the composition of the eruption timeline is most relevant to this chapter. Similarities in temporal scale and data sources (MIROVA, INSIVUMEH bulletins) lend Figure 4.7 as a template for presenting this chapter's results (see Section 4.6).

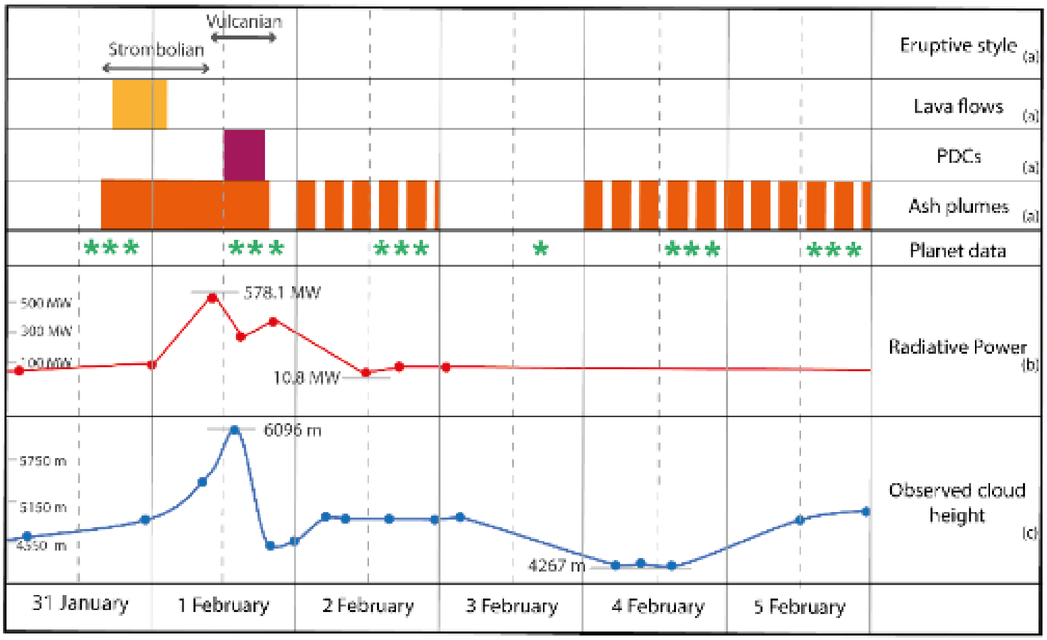


FIGURE 4.7. Multiparametric timeseries chronicles the evolution of a paroxysm at Fuego. The figure shows geophysical patterns and hazards associated with the paroxysm of 31st January - 1st February 2018. From Aldeghi et al. (2019).

4.3.6.2 Using SO_2 to decode eruptive triggers

Several authors have studied SO_2 to decode drivers of eruptive behaviours at Fuego. Figure 4.8 summarizes these findings. The results of each study are explored below.

Crafford [1975] studied SO_2 degassing at Fuego between October and December 1974, including the VEI-4 eruptive episode of 10th - 23rd October. He estimated that a minimum of 220kT SO_2 were ejected during this episode by degassing of the magma chamber, but did not explore the mechanisms by which this occurs. Evidence from other volatile sources suggests that the 1974 eruption may have been triggered by influx of a fresh batch of magma a decade prior to eruption [Berlo et al., 2012]. Andres et al. [1993] used COSPEC measurements to link patterns in degassing with subsurface dynamics driving activity. SO_2 fluxes recorded in 1990 - 1991 were attributed to degassing of a shallow magma body residual's from previous eruptions. While Andres et al. [1993] found increases in SO_2 flux correlated with eruptions of Fuego in 1974 and 1978, fluxes were not found to correlate with changes in eruptive style. Variable magma convection rates, influx of fresh magma, or changes in subsurface plumbing could all explain this apparent lack of correlation [Andres et al., 1993]. In any case, the SO_2 data gathered in this study was insufficient to seriously investigate drivers of eruption. Study of SO_2 degassing in 1999 - 2002 [Rodríguez et al., 2004] had better temporal resolution that allowed deeper exploration of triggers of eruptive activity. This study was fortunately timed as it followed Fuego's reactivation in 1999. Variation in SO_2 degassing was linked to changes in eruptive style and thus eruptive triggers. Volcanic activity increased from December 2001 as Fuego's eruptive style changed from 'fuming' to Strombolian [Rodríguez et al., 2004]. This transition was accompanied by greater SO_2 flux. Both activity and SO_2 degassing increased in February - April 2002 then began to decline in May. This was interpreted as either an increase in the magmatic supply of SO_2 at depth, or greater system permeability caused by fracture propagation and formation of bubble networks, or both Edmonds et al. [2003]. The first explanation invokes a magma-driven model of triggering eruption at Fuego that agrees with my argument in Chapter 2.6.2. Greater system permeability at Fuego could be driven either through influx of fresh magma, or through increased gas supply that does not require new magma to enter the system. Discussion of timeseries data presented in this chapter (see Section 4.7.1.1) hopes to inform the debate on drivers of eruption at Fuego, and identify where future monitoring efforts can reduce uncertainty.

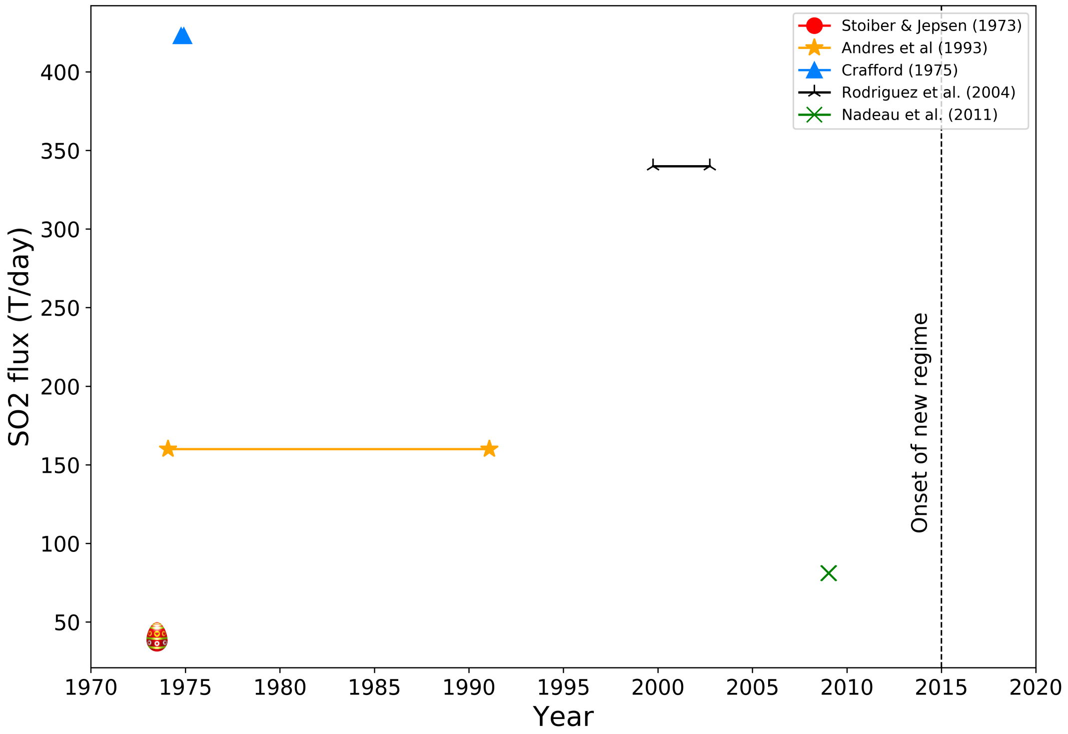


FIGURE 4.8. Previous studies of SO_2 degassing at Fuego and onset of new eruptive regime as described in Chapter 2. Most recent published data is from Nadeau et al. (2011).

The correlation between SO_2 and tremor observed by Rodríguez et al. [2004] was confirmed by Nadeau et al. [2011] after data captured in 2009. Patterns in SO_2 were also related to distinct explosive events. These patterns were explained as a two-stage source process of (1) magma stiffening to form a plug in Fuego's upper conduit to inhibit degassing, followed by (2) pressure under plug overcoming confining pressure to generate ash-rich explosion and increase in SO_2 degassing. Other authors have proposed the "leaky plug" as a driver of multiple eruptive behaviours across a range of timescales (e.g., Waite et al. [2013], Liu et al. [2020]). Meanwhile, monitoring of SO_2 during explosive activity at Fuego could be useful in risk mitigation. Andres et al. [1993] advocated establishing a baseline for SO_2 from which anomalies could be distinguished. It appears Fuego has a low baseline: recent camera measurements of SO_2 flux show that only ~5% is quiescent gas flux, while ~95% is associated with explosive activity [Waite et al., 2013, Burton et al., 2015]. This information could be used in efforts to forecast future eruptions of Fuego by establishing a baseline from which deviations may be significant. This could potentially allow earlier issue of forecast (Figure 4.3).

Recent advancements in satellite data resolution and accessibility have allowed for detection of SO_2 degassing patterns at unprecedentedly high detail. These advances represent a step change in space-based detection of volcanic emissions. At Fuego, analysis of SO_2 timeseries from IASI satellite data estimated that the 3rd June 2018 produced 130 kT of SO_2 [Pardini et al., 2019]. This estimate is comparatively less than the 220 kT estimated for October 1974 [Crafford, 1975], but is nonetheless impressive. This paper contributes to evidence for a magma-driven model of paroxysm at Fuego [Pardini et al., 2019]. From a risk mitigation perspective, improved resolution and accessibility of satellite data are likely to improve INSIVUMEH's capacity to monitor activity and anticipate eruptions. The institution has latterly included satellite data analysis in their monitoring efforts, as stated in Chapter 2.6.4.

A more thorough review of previous SO_2 studies at Fuego, including a table related to Figure 4.8, appears in Appendix K (Chapter 15).

4.3.6.3 Spatial component: hazard maps and evacuation routes

Pyroclastic flow hazard at Fuego is greatest within its seven barrancas. Figure 4.9 shows areas of high (red) and low (yellow) pyroclastic flow hazard around the volcano. This is a preliminary hazard map created after the 3rd June 2018 eruption. The areas of high and low hazard were generated from different eruptive scenarios based on type of eruption and volume of pyroclastic flows generated. The map was created jointly between INSIVUMEH, MTU, USGS/VDAP, and the University of Edinburgh. A description of the software used, HazMapper, appears in Scheip and Wegmann [2020].

Figure 4.10 shows a preliminary map of lahar hazard around Fuego. This map was generated by the same team as Figure 4.9 following the 3rd June 2018 eruption. Colours denote areas of high (red), moderate (orange), and low (yellow) lahar hazard, corresponding to volumes of 10, 20, and 60 x 10^6 m^3. Communities are denoted by black dots, access roads by black lines. This map is the latter of two generated for different rainfall scenarios (A, "moderate rainfall", B "intense

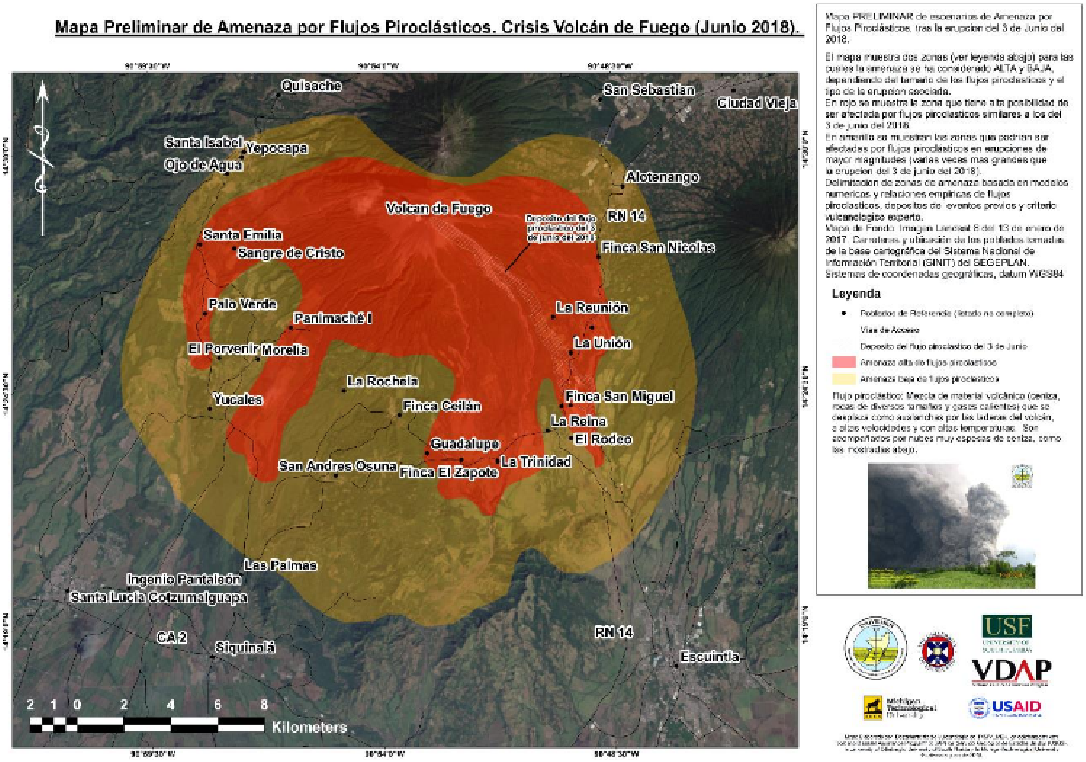
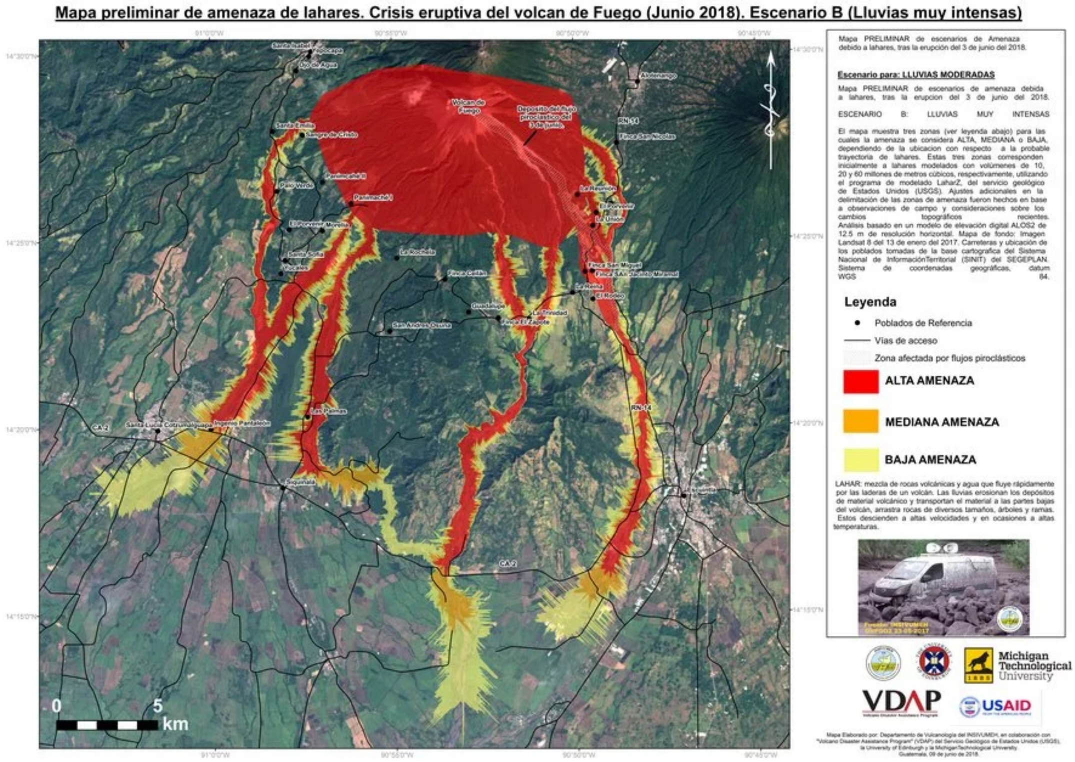


FIGURE 4.9. Map of pyroclastic flow hazards at Fuego, made following the 3rd June 2018 eruption. A joint project between MTU, University of Edinburgh, and HazMapper. Source: `https://www.unige.ch/sciences/terre/CERG-C/files/3015/3209/3528/Fuego_E_Calder.pdf`.

rainfall").

A technical report of concatenated volcanic hazards at Fuego, produced for the World Bank and the Government of Guatemala following the June 3rd June 2018 eruption, can be found at Gavin and Ltd. [2018]. This report includes the two hazard maps presented here and describes both their context and their expected future use in risk mitigation at Fuego.

Figure 4.11 is a map of evacuation routes for communities around Fuego. This map was co-developed by CONRED and the Japanese International Co-operation Agency (JICA), within the project BOSAI, "Desarrollo de Capacidades para la Gestión de Riesgos de Desastres en América Central" (Development of Capacity for Volcanic Risk Management in Central America) [Web, 2017]. Each icon (orange triangle in blue circle) is a radio base staffed by a member of that community's COLRED, a network also established by BOSAI [CONRED, 2013]. Orange and red evacuation routes are south towards Ingenio Pantaleon, blue evacuation route is south towards La Providencia (and onwards to Siquinalá), and yellow evacuation route is east towards El Rodeo (and onwards to Escuintla). Several communities, such as San Andrés Osuna, sit between two



Mapa PRELIMINAR de escenarios de Amenaza debido a lahares, tras la erupción del 3 de junio del 2018.

Escenario para: LLUVIAS MODERADAS

Mapa PRELIMINAR de escenarios de amenaza debida a lahares, tras la erupcion del 3 de junio del 2018.

ESCENARIO B: LLUVIAS MUY INTENSAS

El mapa muestra tres zonas (ver leyenda abajo) para las cuales la amenaza se considera ALTA, MEDIANA o BAJA, dependiendo de la ubicacion con respecto a la probable trayectoria de lahares. Estas tres zonas corresponden inicialmente a lahares modelados con volúmenes de 10, 20 y 60 millones de metros cúbicos, respectivamente, utilizando el programa de modelado LaharZ, del servicio geológico de Estados Unidos (USGS). Ajustes adicionales en la delimitación de las zonas de amenaza fueron hechos en base a observaciones de campo y consideraciones sobre los cambios topográficos recientes. Análisis basado en un modelo de elevación digital ALOS2 de 12.5 m de resolución horizontal. Mapa de fondo: Imagen Landsat 8 del 13 de enero del 2017. Carreteras y ubicación de los poblados tomadas de la base cartografica del Sistema Nacional de InformaciónTerritorial (SINIT) del SEGEPLAN. Sistema de coordenadas geográficas, datum WGS 84.

LAHAR: mezcla de rocas volcánicas y agua que fluye rápidamente por las laderas de un volcán. Las lluvias erosionan los depósitos de material volcánico y transportan el material a las partes bajas del volcán, arrastra rocas de diversos tamaños, árboles y ramas. Estos descienden a altas velocidades y en ocasiones a altas temperaturas.

Mapa Elaborado por: Departamento de Vulcanología del INSIVUMEH, en colaboración con "Volcano Disaster Assistance Program" (VDAP) del Servicio Geológico de Estados Unidos (USGS), la University of Edinburgh y la MichiganTechnological University. Guatemala, 09 de junio de 2018.

FIGURE 4.10. Map of lahar hazards at Fuego, made following the 3rd June 2018 eruption. A joint project between MTU, University of Edinburgh, and HazMapper. Source: `https://blogs.mtu.edu/engineering/2018/06/21/lahars-threats-in-the-aftermath-of-volcan-de-fuego/`.

evacuation routes and may choose either during an eruptive crisis. The decision will be influenced by level of lahar and pyroclastic flow hazard in barrancas in each evacuation route: evacuating west, residents of San Andres Osuna must traverse Barranca Ceniza; evacuating east, they traverse Barranca El Jute.

FIGURE 4.11. Evacuation routes for communities on flanks of Fuego. Created and maintained by CONRED. Picture my own, taken in UPV office on 14/03/2018.

4.4 Hypotheses

Fuego is widely recognized as an open-vent system, in which "gases or pressure from an influx of magma enter the system" [Reath et al., 2019] and escape through the conduit. As at other open-vent systems, patterns in geophysical data can aid forecasting of eruption of Fuego. Previous studies of geophysical data provide guidance for hypotheses of short-term patterns in my data. Understanding temporal frequency and uncertainty associated with these patterns are essential to constrain timescale over which an eruption will develop, and consequently the time available to evacuate.

In Chapter 2, I showed that RSAM was consistently used in INSIVUMEH special bulletins announcing eruption. Therefore it is likely that a sharp increase in RSAM will consistently precede paroxysmal onset for the eruptions studied in this chapter. I also hypothesize that SO_2 flux will increase prior to paroxysmal onset. Pre-paroxysmal increase in SO_2 flux would be consistent with previous observations at Fuego [Rodríguez et al., 2004]. Patterns in geophysical signals prior to the paroxysm of 3rd June 2018 are likely to deviate from these hypothesized patterns. This eruption was exceptional among paroxysms of Fuego for many reasons, including for the volume of material erupted and (potentially) for the absence of precursory lava flows [Pardini et al., 2019]. A lack of increased SO_2 fluxes prior to the 3rd June paroxysm suggests inhibition of pathways for gas release in Fuego's upper conduit. This has been proposed at Fuego on shorter timescales through rheological stiffening of a magma plug in the conduit [Nadeau et al., 2011]. In this way, partial sealing of the upper conduit inhibits the movement of gas bubbles through fractures towards the surface.

Although I predict that RSAM and SO_2 flux values will increase prior to paroxysm, I also predict that these increases will be non-linear and prone to some uncertainty. These increases will occur on the order of hours before paroxysmal climax. Such a timescale will therefore be comparable to timescales of response, which has important implications for the success of the self-evacuation policy. For SO_2 fluxes, while detailed investigation of patterns may inform understanding of eruptive triggering mechanisms, I predict that the timescale over which they vary may be too short to consistently include them as a tool for forecasting of eruption.

4.5 Methods

This chapter explores the evolution of eruptive activity and interactions between geophysical monitoring and multi-stakeholder risk management responses at Fuego since 1999. Analysis is grounded in a review of secondary literature augmented by primary information generated from multiparametric monitoring data from various sources. These data include geophysical datasets for four eruptive events at Fuego within the period examined in Chapter 2. These events comprise three paroxysmal eruptions and one effusive eruption that did not accelerate to paroxysm[1]. Results from analysis of SO_2 data from the NicAIR camera[2] are accompanied by parallel results from satellite and seismic timeseries. This is supplemented by semi-structured interviews conducted in 2018 and 2019 with various stakeholders. Interview data presented in this chapter focus on timescales involved in responses to evacuations from eruptions in 2012 and during the 2015 - 2018 eruptive regime. These interviews were obtained by a mixture of purposive and snowball sampling. A full description of the methods used for interview data appears in 3.5. Additional spatial information comes from hazard maps and evacuation routes created respectively by INSIVUMEH and CONRED.

Data coverage at Fuego was sporadic before 2018. For ~8 years at Fuego the only permanent monitoring equipment was the FG3 seismometer (G. Chigna, pers. comm.) (see Section 4.7). During this period, RSAM from FG3 were the primary data which INSIVUMEH used to forecast short-term changes in eruptive behaviour. Fortunately, additional data are available for several paroxysms within the period 2015 – 2018 that may give new insights on eruptive processes and

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[1] Note that this effusive eruption passes the 200 MW threshold of volcano radiative power defined in Chapter 2, and was therefore included in Table 2.1

[2] A full description of the NicAIR camera parameters appears in Appendix H (Chapter 13), while a full description of the camera set-up appears in Appendix J (Chapter 14).

timescales. Figure 4.12 shows data coverage in 2015 - 2018 for various geophysical datasets. This justifies the choice of eruptions to study (July and September 2016, November 2017, and June 2018). The September 2012 paroxysm was included for study of response timescales due to its frequent appearance in interview data.

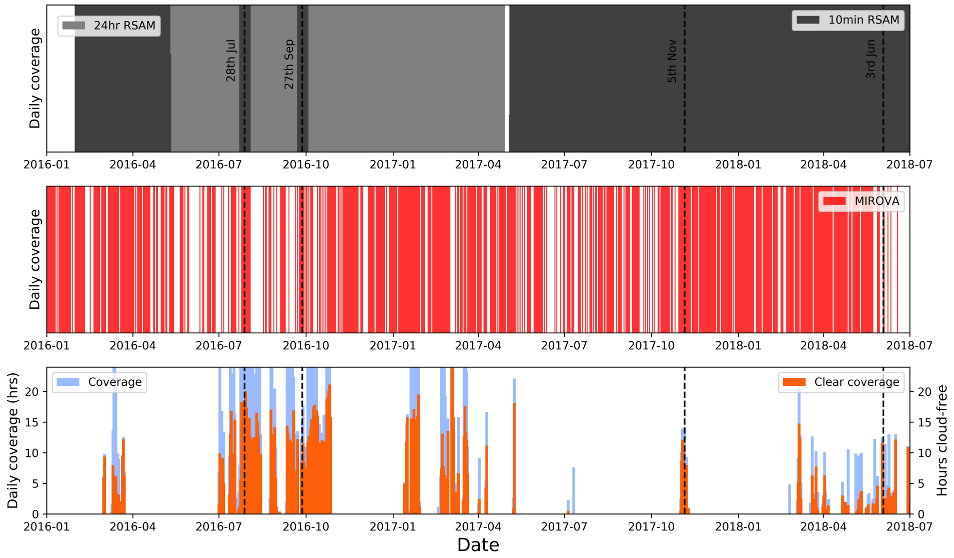


FIGURE 4.12. Coverage of RSAM (top), MIROVA (centre), and NicAIR timeseries datasets, March 2016 - June 2018.

4.6 Results

In this section, results from geophysical monitoring data precede those from other sources including interview and map data. Results of eruption timescales appear in 4.6.1. The section begins with a summary of four eruptions within the 2015 - 2018 cycle (Section 4.6.1) as traced by SO_2 flux and lava/PF coincidence in barrancas (Section 4.6.2). The September 2012 eruption does not appear here as the same datasets were not available. Next, Section 4.6.3 presents findings from each eruption individually. They appear in the following order: July 2016 (Section 4.6.3.1), September 2016 (Section 4.6.3.2), June 2018 (Section 4.6.3.3), November 2017 (Section 4.6.3.4). Section 4.6.4 presents results for timescales of response to eruptions through interview data. Section 4.6.5 pairs eruption and response timelines for September 2012 and June 2018 paroxysms before Section 4.6.6 presents relevant map data to consider how risk varies spatially around Fuego.

4.6.1 Timescales of eruption

Figure 4.13 summarizes eruptive styles, geophysical parameters, and SO_2 fluxes for three paroxysmal and one effusive eruption in 2015 - 2018. Note that vertical axis values are the same for all four eruptions. Eruptive styles have been determined from INSIVUMEH bulletins as follows: ‘Strombolian’ records moderate explosive activity generating ash and ballistics, while ‘Paroxysmal’ records powerful explosive activity and associated hazards. SO_2 fluxes from both horizontal and vertical transects are shown. The specific method for capturing SO_2 appears in Appendix 11. Both transects were included because of the variability of Fuego’s eruptive plume, which can move from near-horizontal to vertical during a day’s data capture. All times are local unless stated otherwise.

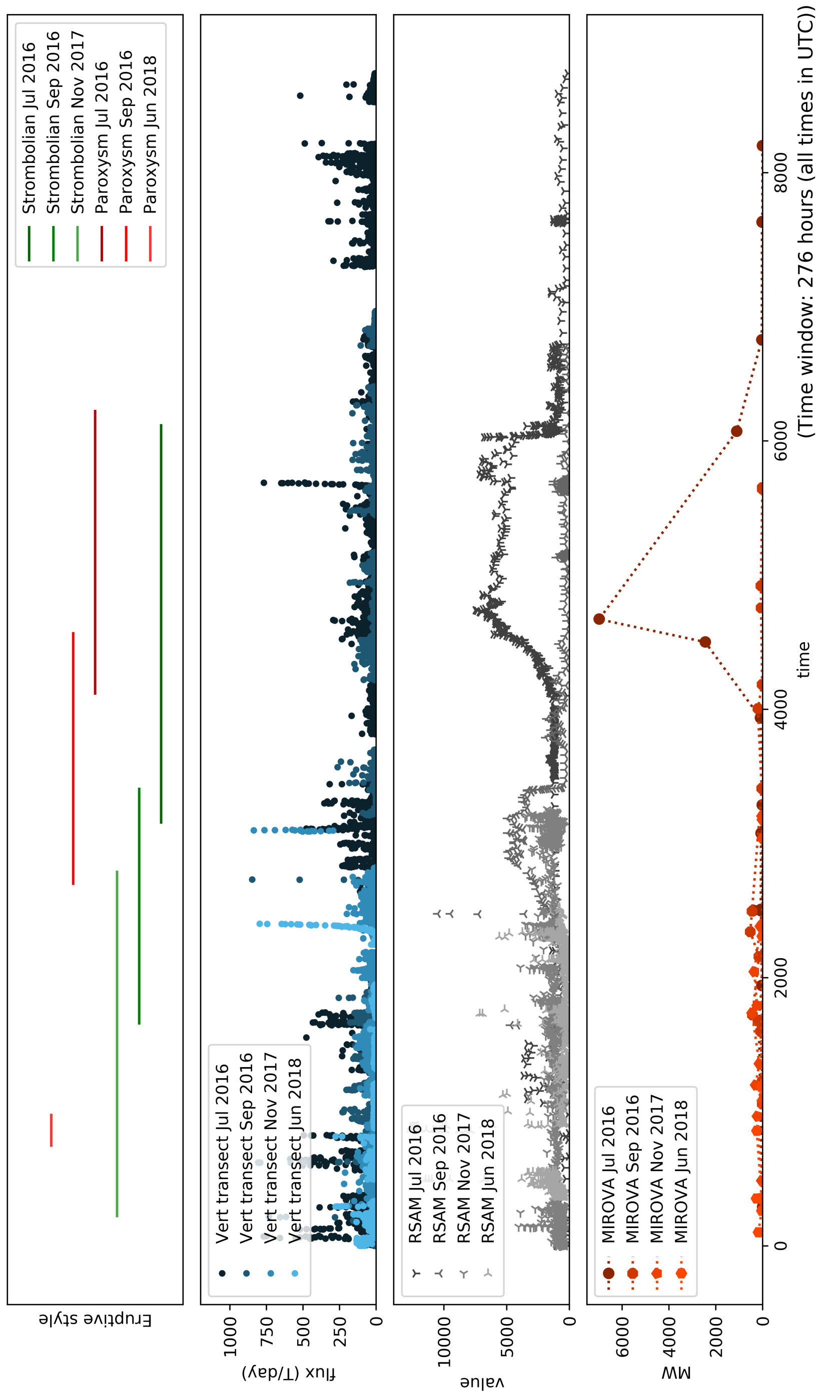
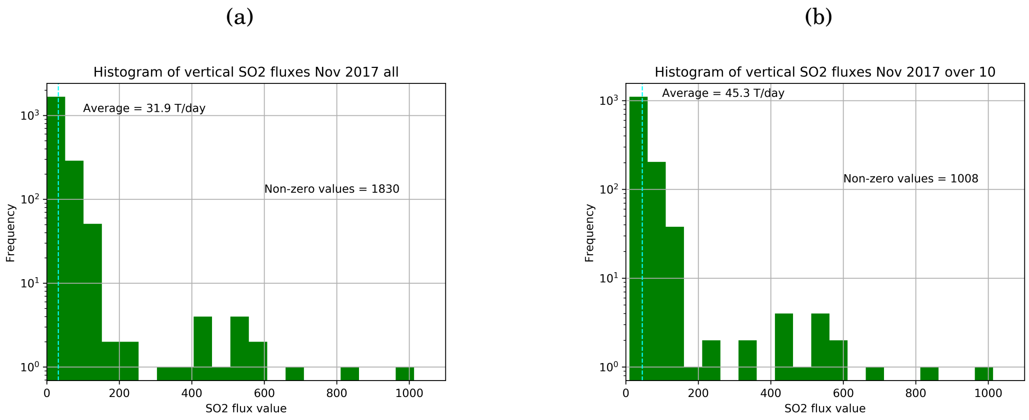


FIGURE 4.13. Master timeseries plot comparing eruptive styles, duration, and relative magnitudes of SO_2, RSAM, and MIROVA for four eruptions studied in this section. Time window of 276 hours (given in bottom right) is for the July 2016 paroxysm, which had the greatest temporal coverage of the four eruptions studied in this chapter.

Table 4.1 gives daily average SO_2 flux values as well as maximum and minimum daily flux values and one standard deviation (S.D.) for four eruptions in the 2015 - 2018 eruptive cycle studied in Chapter 2. While SO_2 data can be weighted (i.e., readjusted to reflect number of measurements or confidence in them) to improve accuracy, data weighting is itself somewhat subjective. The most accurate way to improve validity is to increase temporal resolution and coverage, but this was not possible in this project. Thus I have followed the guidance of Rodríguez et al. [2004] and given unweighted averages. Fluxes include days of eruption and several days surroundings. A large number of images produced negligible SO_2 fluxes of <10 T/day. On investigating, these fluxes were caused by cloudy images not captured by the cloud-filtering script (see 11). Therefore, fluxes of <10 T/day have been excluded from Table 4.1 and Figure 4.15. Figure 4.14 illustrates the difference. Figure 4.14(a) shows the number and distribution of flux values for the November 2017 effusive eruption. Many are negligible (0 - 10 T/day). When values <10 T/day are excluded, the dataset size drops significantly (from 1830 to 1008 values), but the distribution of values remains similar (Figure 4.14(b)). Meanwhile, the daily average SO_2 flux increases. In Table 4.1, eruptive style for that day is included where possible. Eruptive style information came from INSIVUMEH special bulletins and the Smithsonian website. Colours in Table 4.1 correspond to individual eruptions and their results presented in Section 4.6.3.



(a) (b)

FIGURE 4.14. Comparison of distributions of SO_2 flux values for November 2017. (a) All non-zero values included. (b) Only values ≥10 T/day included.

Date	Avg SO_2 (T/day)	Min SO_2 (T/day)	Max SO_2 (T/day)	S.D. (T/day)	Activity
25/07/2016	100	10	769	117	
26/07/2016	57	10	478	80	strombolian
27/07/2016	21	10	109	15	strombolian
28/07/2016	68	10	477	79	strombolian
29/07/2016	58	10	774	103	paroxysm
30/07/2016	31	10	192	21	paroxysm then minor explosive
31/07/2016	39	10	316	38	
01/08/2016	56	10	1076	76	
02/08/2016	23	0	250	28	
03/08/2016	17	0	200	29	
04/08/2016	12	0	190	24	
06/08/2016	19	0	522	39	
07/08/2016	18	0	364	37	
18/09/2016	34	0	303	48	
20/09/2016	28	0	241	40	
21/09/2016	95	10	807	170	
22/09/2016	41	10	255	40	strombolian
26/09/2016	55	10	256	41	strombolian
27/09/2016	29	10	853	73	strombolian
28/09/2016	36	10	263	40	paroxysm
29/09/2016	34	10	149	27	
30/09/2016	39	10	180	31	
02/10/2016	36	10	182	42	
03/10/2016	34	10	196	30	paroxysm
04/10/2016	22	0	243	39	strombolian
05/10/2016	31	0	301	54	major explosive
06/10/2016	13	0	351	31	
07/10/2016	15	0	342	37	
03/11/2017	33	10	219	30	strombolian
05/11/2017	43	10	201	27	strombolian
06/11/2017	41	10	157	29	strombolian
07/11/2017	39	10	201	29	seething
09/11/2017	533	294	1013	157	quiet
28/05/2018	54	10	284	50	
02/06/2018	26	10	83	15	
03/06/2018	134	10	518	132	
04/06/2018	13	10	22	3	
05/06/2018	13	10	31	4	
06/06/2018	15	10	35	5	
08/06/2018	131	10	1628	226	
09/06/2018	69	10	1100	219	
11/06/2018	69	0	789	102	explosive
12/06/2018	12	0	120	16	explosive
14/06/2018	17	0	135	21	

Table 4.1: Daily averages, minimum and maximum flux rates, and standard deviation (S.D.) for days with paroxysmal eruption and beyond in new eruptive regime. Colours complement individual eruptions studied in Section 4.6.3.

Figure 4.15 shows cumulative SO_2 fluxes for the four eruptions studied. Stars indicate day of paroxysmal onset as derived from INSIVUMEH bulletins. Day 0 represents the first day of SO_2 coverage from NicAIR (see Figure 14.4). SO_2 values for paroxysms were obtained during NicAIR's deployment at La Reunión golf resort, while values for November 2017 were obtained during deployment at OVFGO1 (with additional data from terraces of Volcán Acatenango on 3rd and 5th Nov 2017) (see Figure 14.3 for locations). Each paroxysmal eruption follows a similar slope. Onset occurs at Day 5 (Jul 2016 paroxysm), Day 10 (Sep 2016 paroxysm), and Day 7 (Jun 2018 paroxysm). The greatest output for July 2016 occurs on 25th July (pre-paroxysmal, 100 T/day), for September 2016 on 21st September (pre-paroxysmal, 95 T/day), and for June 2018 on 9th June (post-paroxysmal, 182 T/day). Pre-paroxysmal fluxes are between 21 - 100 T/day (Jul 2016), 28 - 95 T/day (Sep 2016), and 26 - 54 T/day (Jun 2018), while during paroxysm SO_2 fluxes range between 31 - 68 T/day (Jul 2016), 34 - 36 T/day (Sep 2016), or reach 135 T/day for 3rd June 2018. Post-paroxysmal fluxes show lowest SO_2 values but also the greatest variability at 12 - 56 T/day (Jul 2016), 13 - 39 T/day (Sep 2016), or 13 - 182 T/day (Jun 2018). The November 2017 effusive eruption follows a different trend, with a smaller slope gradient indicating less SO_2 degassing. This trend discontinues with a sharp increase in degassing on 9th November. However, deployment on 9th November was much shorter, consisting of a 15-minute sequence which produced an average flux of 533 T/day. More detail is given in Section 4.6.3.4.

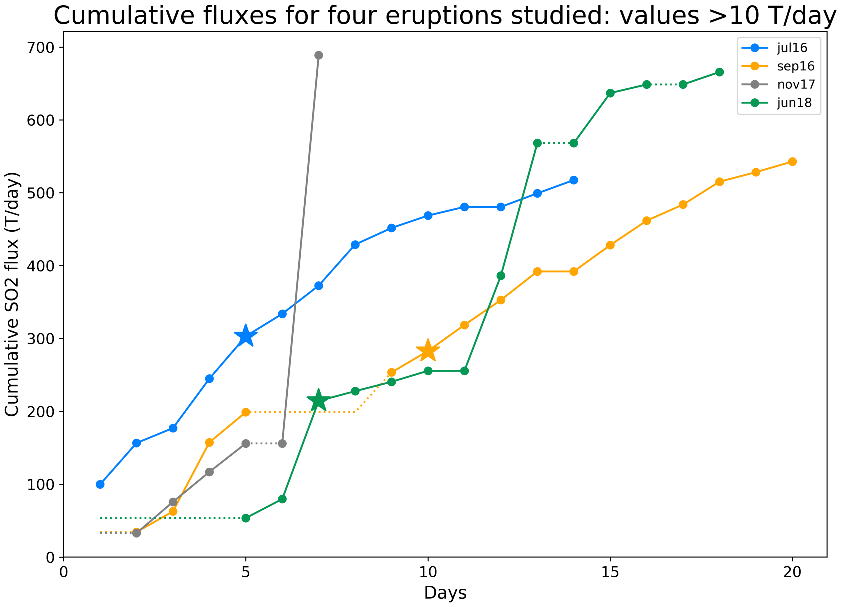


FIGURE 4.15. Cumulative SO_2 degassing trends for three paroxysms (Jul 2016, Sep 2016, Jun 2018) and effusive eruption (Nov 2017). Star indicates paroxysmal onset day. Dashed sections represent days of apparent null flux, but may be false negative due to ash.

Figure 4.16 shows daily averages of SO_2 fluxes and VRP values for a nine-week period that includes the paroxysms of July and September 2016. Peaks in VRP values coincide well with paroxysmal onset (as seen in Chapter 2). VRP values drop rapidly following paroxysm. SO_2 fluxes are less consistent. For the July paroxysm, flux values decrease towards paroxysmal onset and in the days after. A large data gap in August 2016 is associated with both camera operational failures and high cloud cover during peak rainy season. SO_2 values also decrease towards day of paroxysmal onset for the September paroxysm. However, the tall vertical bars for daily SO_2 fluxes show the large uncertainties associated with these values.

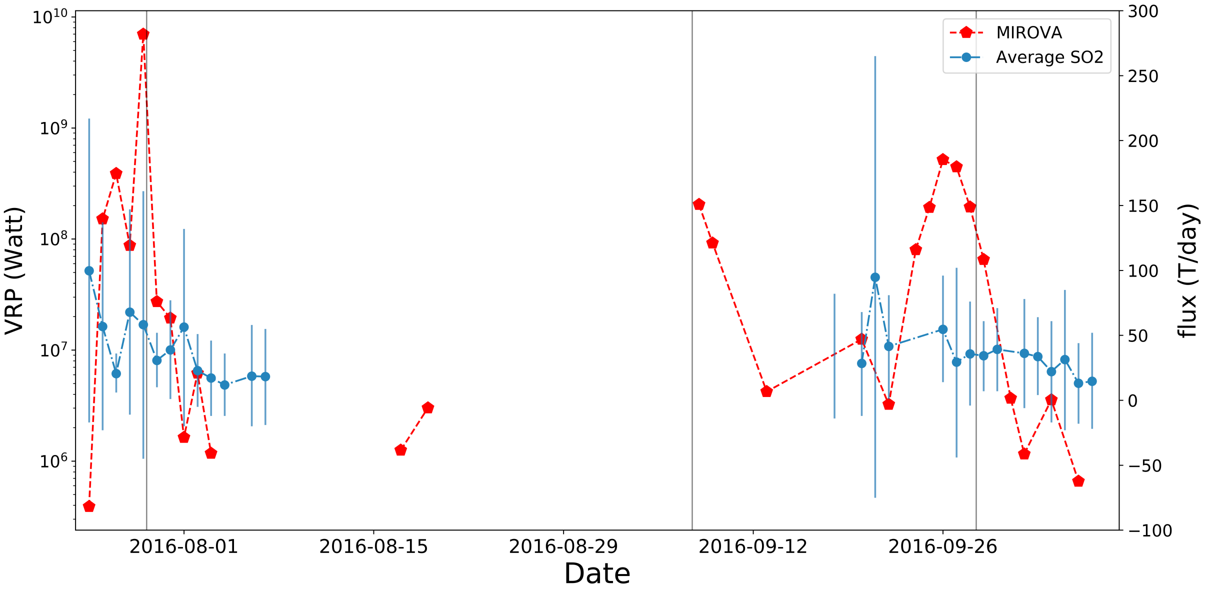


FIGURE 4.16. Daily SO_2 averages and MIROVA for July through October 2016. Vertical blue bars give 1 standard deviation (SD) from average SO_2 flux. Vertical grey lines represent INSIVUMEH special bulletins reporting onset of paroxysmal eruption.

4.6.2 Lava and pyroclastic flow coincidence

There is a very strong correlation between lava flow and pyroclastic flow travel direction in the 2015 - 2018 eruptive regime. Of the 41 paroxysmal eruptions that occurred between January 2015 and June 2018[3], 18 were preceded by lava effusion and produced pyroclastic flows and 23 were preceded by lava effusion but did not produce pyroclastic flows. Only one paroxysm produced pyroclastic flows and was not preceded by lava effusion (18th May 2017). Given that a paroxysm at Fuego in 2015 - 2018 is characterized by precursory lava effusion and pyroclastic flows (Chapter

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[3] See Table 2.1 of Chapter 2 for list of paroxysms January 2015 – June 2018. Paroxysms are slightly different between this analysis and that of Chapter 2 due to: (i) exclusion from Chapter 2 of 18th May 2017, as it did not meet the MIROVA detection threshold; (ii) exclusion from this table of 3rd June 2018, due to uncertainty regarding lava effusion.

2, it is unsurprising that no paroxysms occurred that involved neither of these hazards. The 18 paroxysms involving both precursory lava effusion and pyroclastic flows are identified in Table 4.2. These show a strong correlation between direction of lava effusion and the barranca in which pyroclastic flows descended. As Chapter 2.5 showed, lava flows at Fuego in 2015 – 2018 rarely exceed 3 km (see Table 2.1), so that flows rarely extend into individual barrancas. Nevertheless INSIVUMEH reports direction of travel of lava flows, and Table 4.2 indicates that direction of lava flow travel towards a barranca corresponds strongly to subsequent descent of pyroclastic flows in the same barranca. Only three exceptions occur: descent of pyroclastic flows in Barranca El Jute in the 2nd January 2016 paroxysm, in Barranca Trinidad in the 4th May 2017 paroxysm, and again in Trinidad during the 31st January 2018 paroxysm.

No.	Start date	Lava flow	Pyroclastic flow	PF barranca not specified	PF in barranca without lava
1	08/02/2015	EJ, TD	EJ, TD		
5	01/07/2015	LL	LL		
7	01/09/2015	ST, TD		X	
9	26/10/2015	LL, ST, TD	LL		
11	29/11/2015	CZ, HO, LL, ST, TD	HO		
12	15/12/2015	ST, TD		X	
13	02/01/2016	LL, ST, TD	EJ, LL, TD		EJ
14	20/01/2016	EJ, LL, ST, TD	EJ, LL		
15	08/02/2016	LL, TD		X	
16	02/03/2016	HO, LL	LL		
21	22/05/2016	LL	LL		
23	27/07/2016	LL, ST	LL, ST		
28	20/12/2016	LL, ST, TY	TY		
32	04/05/2017	LL, ST	LL, ST, TD		TD
33	06/06/2017	CZ, ST	ST		
36	19/08/2017	CZ, ST	ST		
37	14/09/2017	ST	ST		
40	31/01/2018	HO, LL, ST	HO, LL, ST, TD		TD

Table 4.2: Correlating direction of flows for the 18 paroxysmal eruptions in January 2015 – November 2018 that included both precursory lava effusion and pyroclastic flow generation. Initials denote barrancas: CZ (Ceniza), EJ (El Jute), HO (Honda), LL (Las Lajas), ST (Santa Teresa), TD (Trinidad), TY (Taniluyá). **PF barranca not specified** shows where INSIVUMEH reported pyroclastic flows but did not specify the barranca. **PF in barranca without lava** records, for a paroxysm, any barrancas in which pyroclastic flows descended without previous lava effusion.

4.6.3 Individual eruptions

While Figure 4.13 gave results for four eruptions in 2015 - 2018 using the same vertical scale, the individual eruption timeseries in this section have different vertical axes due to the variable maxima that geophysical data reach for each eruption. Note that results from individual eruptions are not presented in chronological order: paroxysmal eruptions are studied chronologically (July 2016, September 2016, June 2018) before the effusive eruption of November 2017. Plots follow the template used in Aldeghi et al. [2019] (see Figure 4.7). Coloured boxes surrounding each plot correspond to SO_2 fluxes in Table 4.1. Eruptive styles have been derived from INSIVUMEH bulletin reports as for 4.13. SO_2 fluxes from both horizontal and vertical transects are shown. All times are local unless stated otherwise.

4.6.3.1 July 2016 (blue)

Fuego had two paroxysms in July 2016 [Venzke, 2013]. The second began on 28th July 2016 and lasted approximately 48 hours. Activity began with frequent ash explosions feeding an eruptive column reaching 5.5 km altitude, and lava fountaining reaching 500 m above Fuego's crater [Venzke, 2013]. Summit activity fed two lava flows in Barrancas Santa Teresa (1.5 km) and Las Lajas (3 km). The first pyroclastic flow descended Barranca Santa Teresa at 12:00 on 29th July, followed by several more. The Washington VAAC recorded a maximum plume altitude of 6.7 km on 29th July. Meanwhile, MODVOLC reported thermal anomalies at Fuego between 26th July and 31st July; the day of highest activity (29th July) produced 17 thermal anomalies [Venzke, 2013].

Figure 4.17 shows the eruption timeline from 25th July to 2nd August. The timeline is bordered by PNG images from NicAIR's broadband channel illustrating the evolution of the eruption. Figure 18a shows eruptive styles. Figure 18b traces SO_2 flux. A single maximum SO_2 flux value of 1076 T/day occurred on 1st August, although values of >600 T/day consistently appeared on 25th and 29th July. Figure 18c shows RSAM. RSAM does not exceed 1200 until 17:44 on 25th July, which records a value of 2107. High (>3000) RSAM values are recorded inconsistently throughout the evening of 25th July. RSAM values of 1000 – 1500 persist until 22:30 on 28th July, when values increase steadily towards a maximum of 7475 at 14:22 on 29th July. The maximum MIROVA value (6974 MW[4]) for the eruption occurs at 07:15 on 29th July. Both RSAM and MIROVA values drop rapidly towards the later hours of 29th July. The "runaway" trend observed in SO_2 is likely associated with either instrumental failure associated with high afternoon temperatures affecting NicAIR (for further discussion, see Section 4.7.1.1). RSAM values do not exceed 1500 from 30th July. However, SO_2 fluxes on 1st August are moderately high (300 – 350 T/day).

Figure 4.18 shows the same datasets for a shorter period (00:00 – 18:00 on 29th July) during

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[4] This value is also the highest MIROVA value recorded for the entire database of MIROVA values 2000 – 2018.

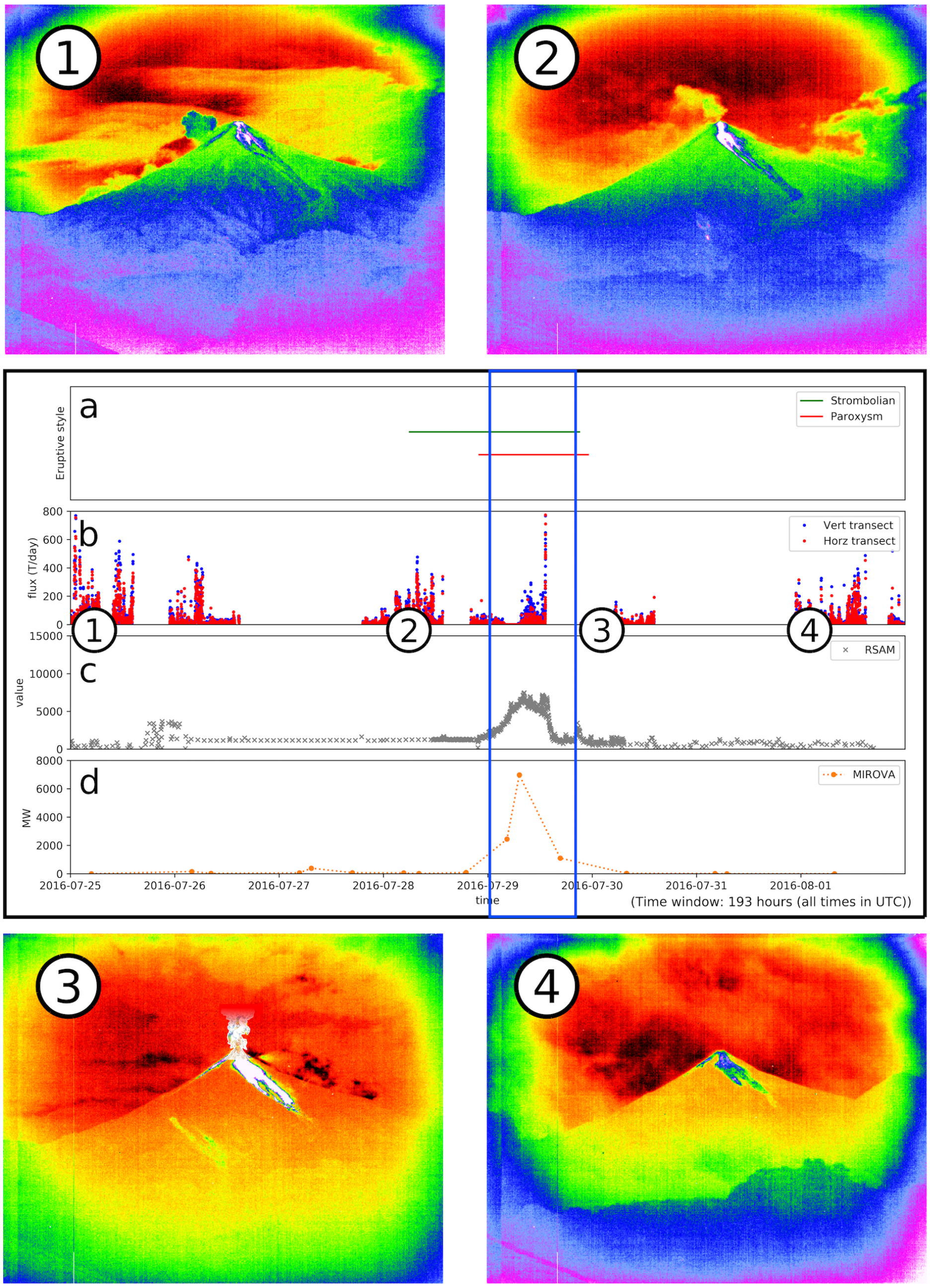

FIGURE 4.17. Multiple timeseries plot for paroxysmal eruption beginning 28th July 2016. From top to bottom, each plot represents: (a) eruptive style derived from INSIVUMEH bulletins; (b), SO2 fluxes derived from NicAIR capture; (c) RSAM from INSIVUMEH's FG3 seismometer; (d) VRP values from MIROVA. Style of plot after Aldeghi et al. (2019). Blue box outlines 18-hour time window shown in Figure 4.18.

paroxysmal climax. Figure 19a shows current eruptive styles. Figure 19b traces SO_2 flux. Flux values are very low between 04:00 – 08:00 on 29th July. Investigation of NicAIR broadband images reveal summit cloud during these hours. This is the most likely source of very low SO_2 fluxes. After this period, fluxes increase rapidly towards a peak of 774 T/day at 13:16. In contrast to the increase in SO_2 during this period, RSAM values decrease.

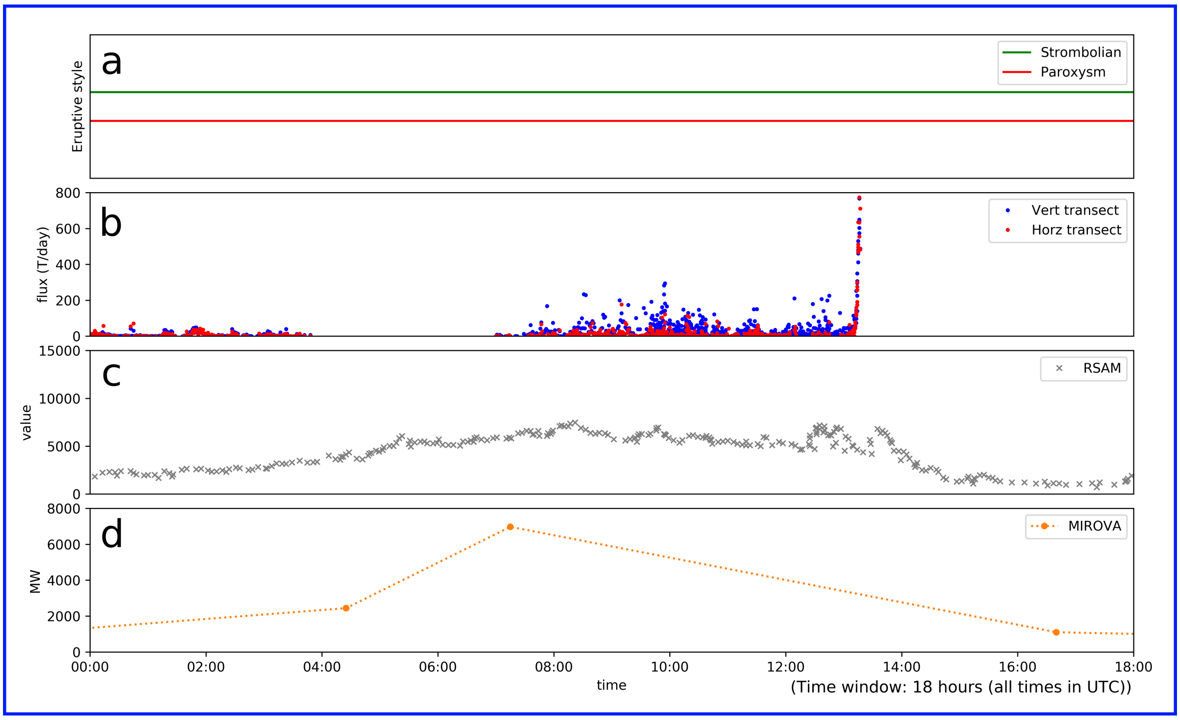

FIGURE 4.18. Multiple timeseries data for 29th July 2016 00:00 – 18:00. Time period shown is within Figure 4.17 blue box.

Figure 4.18 shows an 18-hour window of activity during the paroxysm. This allows study of timescales over which activity evolves. RSAM increases over a 16-hour window (22:00 on 28th July - ~14:00 on 29th July), a period that encompasses increases in summit explosive activity (00:00 - 12:00), paroxysmal climax (08:00 - 14:00), and descent of pyroclastic flows (12:00 - ~14:30). VRP values show a sharp increase over a smaller timescale during acceleration to paroxysm (a 4-hour window, 04:00 - 08:00). SO_2 values were not available for this period, but were noticeably greater in a 5-hour window during paroxysmal climax (08:00 - 13:00).

Narrower focus on data from Figure 4.18 allows study of paroxysmal climax. Figure 4.19 shows only SO_2 and RSAM values at 09:00 – 13:00 on 29th July. Only vertical transect values are included because the plume was near-horizontal at this time. SO_2 flux peaks appear at 09:30 – 10:00 and 12:30 – 13:00. A peak in RSAM slightly precedes SO_2 flux increases at 09:40. However, increases in RSAM and SO_2 are simultaneous at 12:30 and last approximately the same time. A brief decrease in RSAM and SO_2 can be observed around 13:00. However, while SO_2 increases sharply at 13:10, RSAM values continue to decrease. The SO_2 increase unaccompanied by RSAM increase may be an instrumental error, as discussed in Section 4.7.1.1.

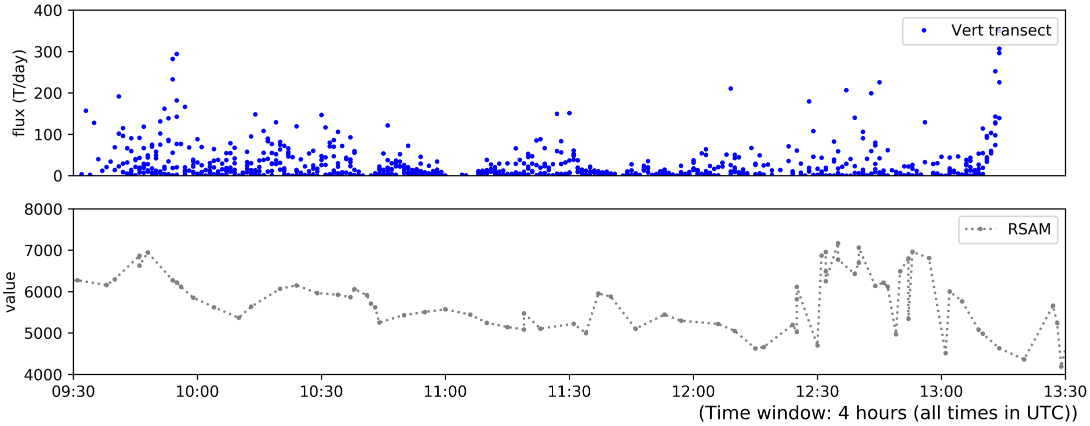

FIGURE 4.19. SO_2 fluxes and RSAM for 09:00 – 13:00 on 29th July 2016. This sequence represents the peak of paroxysmal activity.

4.6.3.2 September 2016 (orange)

INSIVUMEH reported a paroxysmal eruption occurring on 27th and 28th September 2016. Observers at OVFGO1 first noted an increase in activity on 24th September, when lava fountaining rose to 200m above Fuego's crater and a lava flow in Barranca Las Lajas reached 3.5 km (INSIVUMEH bulletin #177-2016). Between 25th and 26th September, incandescent activity dropped slightly while accumulated volcanic material combined with heavy rainfall produced voluminous lahars in multiple barrancas. Increasing explosive activity on the morning of 27th September led INSIVUMEH to declare the beginning of an eruption at 07:30 (INSIVUMEH bulletin #180-2016). The lava flow towards Barranca Las Lajas continued to grow, fed by powerful lava fountaining at summit vents which was accompanied by increasing explosive activity. Explosion rates, lava fountain height, and lava flow length continued to grow during the day (INSIVUMEH bulletin #182-2016, 16:10), and sustained explosive activity at the summit led to a maximum eruption column height of 5000 m altitude. On the afternoon of 27th September, there were two active lava flows: 1500 m in Barranca Las Lajas, and 1800 m in Barranca Santa Teresa. The lava flow towards Santa Teresa reached a maximum length of 2000 m at 21:00 on 27th September. This represented the approximate time of paroxysmal climax, when lava fountaining reached a maximum height (300 m above Fuego's summit) and observers at OVFGO1 reported the largest and most frequent summit explosions (INSIVUMEH bulletin #183-2016 at 21:00. Activity declined throughout 28th September, leading INSIVUMEH to declare the eruption over on this day.

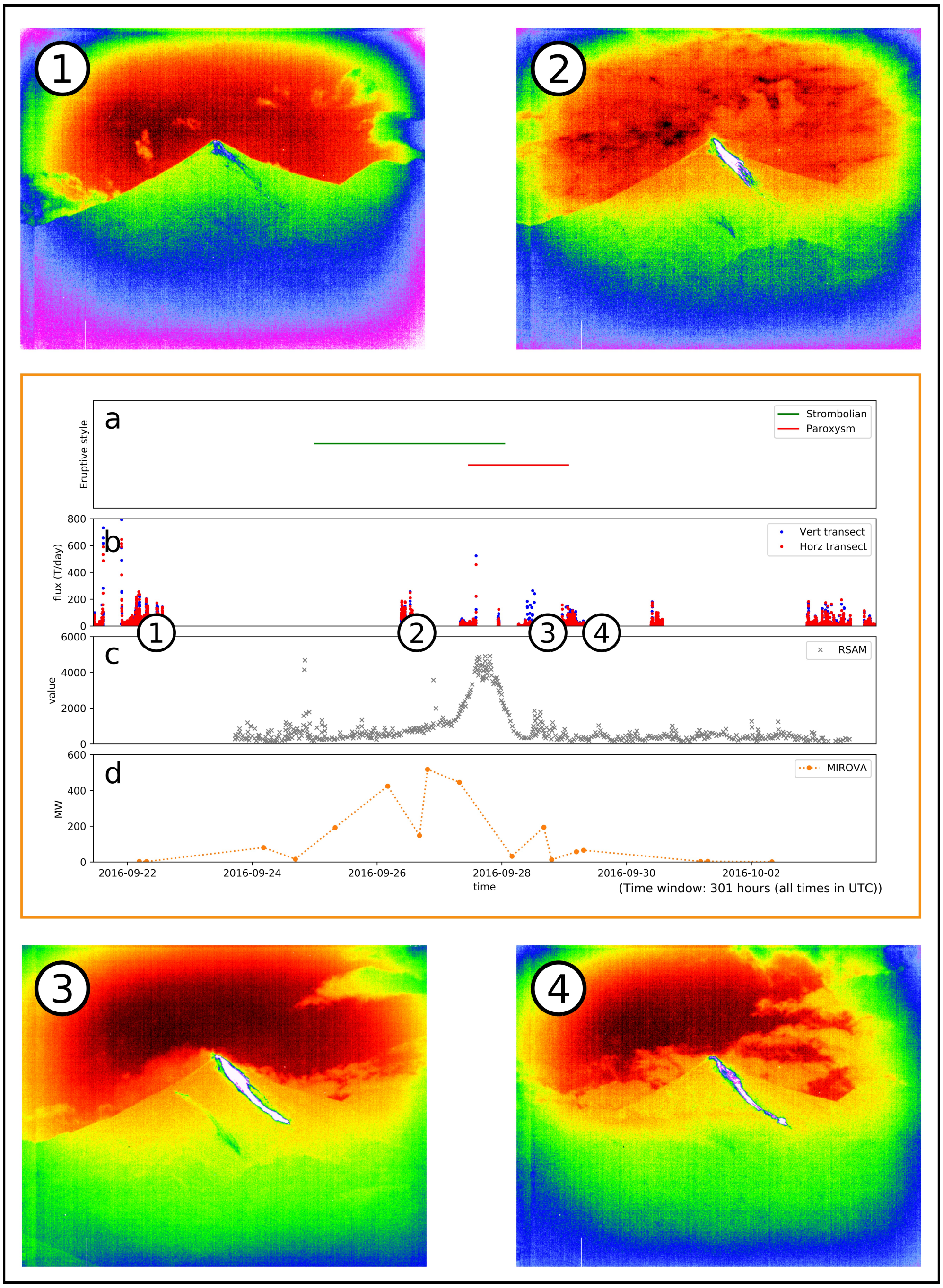

FIGURE 4.20. Multiple timeseries plot for paroxysmal eruption beginning 27th September 2016. Top – bottom: (a) eruptive style; (b), SO_2 fluxes; (c) RSAM; (d) VRP values. Sources as from Figure 4.17.

Figure 4.20 gives values of SO_2, RSAM, and MIROVA for the September 2016 paroxysm. As for July 2016, the timeseries is bordered by images from NicAIR's broadband channel that illustrate the evolution of the eruption. Figure 4.20(a) shows eruptive styles. [5] Figure 4.20(b) shows SO_2 values for the period of 22nd September – 4th October. Values are low, the majority under 200 T/day. Values between 27th – 29th September are negligible (<10 T/day). Figure 4.20(c) shows RSAM over the period 24th September – 3rd October. RSAM seems to slowly increase, apart from anomalous values on 25th September at 18:10 and 26th September at 22:00. RSAM steadily increases from 2200 at ~10:00 on 27th September to reach a local maximum of 5064 at 19:27, before gradually declining to typical values of <2000 at 00:50 on 28th September. Figure 4.20(d) shows a slight increase in VRP values from MIROVA that leads increases in the other timeseries. The first high thermal value of 424.3 MW occurs on 26th September at 04:05 and the second of 445.5 MW at 27th September at 07:40. MIROVA values return to under 200 MW (the threshold for detecting paroxysmal eruption defined in Chapter 2) by 28th September.

Timeseries do not evolve in parallel in this paroxysm. RSAM increases over a 12-hour window (10:00 - 22:00) on 27th September, a period that encompasses acceleration to paroxysm (10:00 - 18:00) and paroxysmal climax (18:00 - 22:00). RSAM declines rapidly over 2.5 hours (22:00 - 00:30 on 28th). VRP values evolve over a much greater timescale than in July: over ~48 hours, from a first high of 192.5 MW at 07:50 on 25th to 445.5 MW at 07:40 on 27th September. If including the value of 194.3 MW at 16:10 on 28th September, this timescale of eruptive evolution increases to 80 hours (~3.5 days). SO_2 values were not available for this period, but were noticeably greater in a 6-hour window during paroxysmal climax (08:00 - 13:00).

4.6.3.3 June 2018 (pink)

INSIVUMEH reported an increase in summit explosive activity at 06:00 on 3rd June 2018 [Venzke, 2013]. Ash plumes rose above the crater and INSIVUMEH reported pyroclastic flows descending Barranca Santa Teresa at approximately 07:00. However, gathering cloud occluded further observation of the summit. The Washington VAAC reported an eruptive plume reaching 9 km at 11:30. In a special bulletin released at 13:40, INSIVUMEH reported pyroclastic flows in all barrancas except Trinidad. Tephra fell <25 km away, including in San Miguel Dueñas (10 km NE), Alotenango, and Chimaltenango (21 km NNE). Ashfall was reported as far away as Guatemala City. Explosions rattled structures within 20 km of Fuego. The La Aurora International Airport closed at 14:15. Eyewitness accounts described the fast-moving pyroclastic flows inundating fields people were working in, overtaking bridges, and burying homes up to their roof lines in some areas. San Miguel Los Lotes, Alotenango, and El Rodeo (10 km SSE) were the worst affected [Venzke, 2013]. INSIVUMEH reported a return to normal levels of activity on 4th June. However, activity increased again on 5th June, with 8 - 10 explosions every hour. At 19:30 on 5th June there was a pyroclastic flow in Barranca Las Lajas [Venzke, 2013].

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[5] These figures include a colour scale where - confusingly - red corresponds to cooler surface temperatures, blue and purple to warmer.

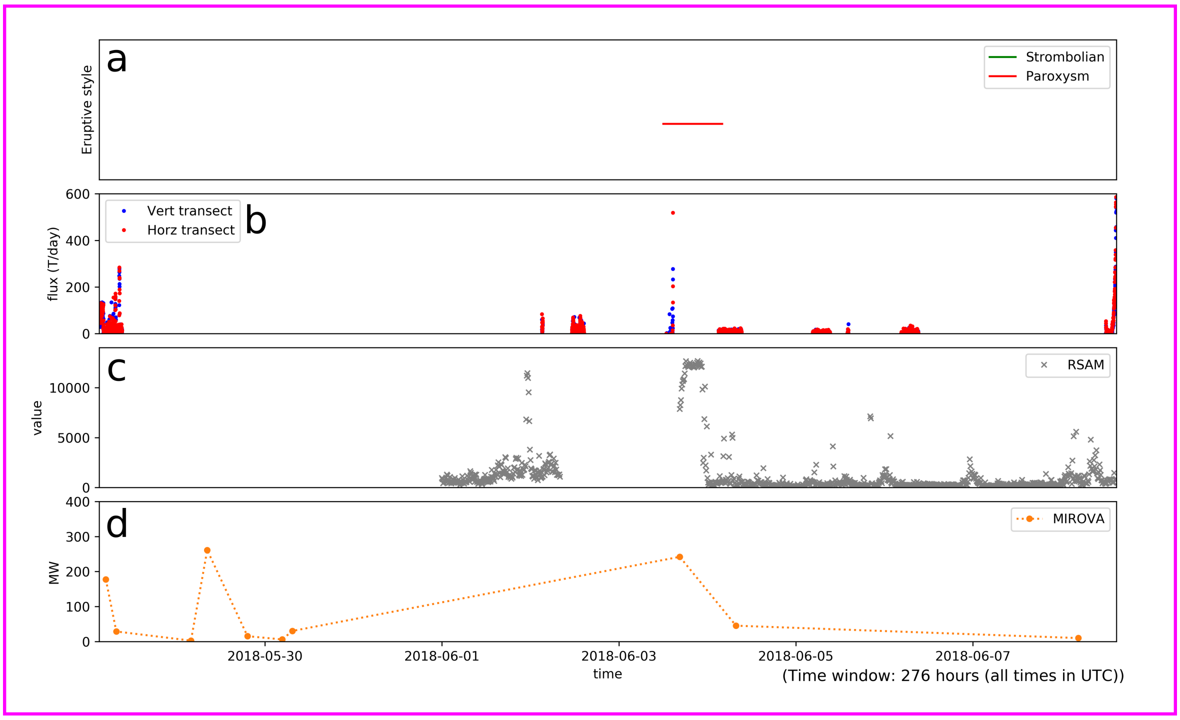


FIGURE 4.21. Multiple timeseries plot for paroxysmal eruption beginning 3rd June 2018. Top – bottom: (a) eruptive style; (b), SO_2 fluxes; (c) RSAM; (d) VRP values. Sources as from Figure 4.17.

Values of SO_2, RSAM, and MIROVA for the eruption of June 2018 are shown in Figure 4.21. Data coverage is patchy due to cloud cover (affecting eruptive style, SO_2, and MIROVA) and instrumental failure (affecting FG3 seismometer - see Section 4.7.1.1 for more detail). Despite poor coverage, the data include values that illustrate the atypical nature of this eruption among recent paroxysms of Fuego. RSAM values of >12000 occurred consistently throughout 3rd June. For comparison, the largest RSAM value recorded outside of the June 2018 paroxysm was 7475 at 08:22 on 29th July 2016. The difference in RSAM of >4500 demonstrates the extraordinary explosive energy of the 3rd June 2018 eruption. Relatively large SO_2 values were measured on 3rd June in comparison to surrounding days. A local maximum of 204 T/day occurred on 3rd June at 14:38 (although note much greater values on 8th June).

Unfortunately, the scarcity of coverage make it difficult to assess through geophysical datasets the timescale over which activity evolved. Cloud cover and connectivity issues prevented capture of RSAM and VRP values during acceleration to paroxysm that may have occurred on 2nd and the early hours of 3rd June. INSIVUMEH report that only one of Fuego's two seismometers was functioning at this time, and became so saturated with data that it collapsed Alvarez [2019]. Timescales can be estimated from INSIVUMEH bulletins. The first Special Bulletin released on 3rd June (INSIVUMEH bulletins #027-2018 at 06:00) records strong explosive activity and pyroclastic flows, marking the onset of paroxysm. Pyroclastic flows continued throughout the morning and early afternoon (INSIVUMEH bulletins #028-2018 and #029-2018 at 10:00 and 13:45), intensifying mid-afternoon as pyroclastic flows descended Barranca Las Lajas and buried San Miguel Los Lotes between 15:00 and 15:20 [Ferres and Escobar, 2018]. Activity decreased during the evening INSIVUMEH reported the end of eruption at 22:00 (INSIVUMEH bulletin #033-2018). This gives an eruption timescale of ~16 hours for paroxysm, from onset at 06:00 to the climax between 12:00 and 16:00, through descent until the eruption ended at 22:00. Acceleration to paroxysm is not included in this timescale.

4.6.3.4 November 2017 effusive eruption (green)

INSIVUMEH reported an increase in activity on 3rd November 2017, and declared the start of an effusive eruption on 5th November at 19:30 (INSIVUMEH bulletin #170-2017). At the time eruption onset was reported, Fuego was producing 6 – 8 explosions per hour, an eruptive column reaching 4800m asl, and two lava flows towards Barrancas Santa Teresa (1000m) and Ceniza (600m). At 12:30 on 6th November, continuous lava fountaining further fed the flows in Santa Teresa (1200m) and Ceniza (800m). At this time the volcano appeared to maintain a constant eruptive energy (INSIVUMEH bulletin #173-2017). INSIVUMEH announced the end of the eruption at 07:00 on 7th November, reporting the remnants of two lava flows in Barranca Santa Teresa (1000m) and Ceniza (800m), 6 – 8 explosions per hour and an eruptive column reaching 4800m asl.

Values of SO_2, RSAM, and MIROVA for the eruption of November 2017 are shown in Figure 4.22. Figure 24b shows SO_2 values for all days of capture: 3rd, 5th – 7th, 9th of November. SO_2 flux values are consistently under 200 T/day except for 9th November, when flux ranges between 294 – 1013 T/day. Figure 24c shows RSAM for this same period. RSAM fluctuates markedly between 171 – 4031 but follows a broad, slow increase and similar decline. MIROVA values also fluctuate considerably (Figure 4.22). There is a gradual increase from 212.3 MW on 3rd November at 16:50 towards a maximum of 443.2 MW on 5th November at 16:40, before a rapid decline in activity. Two VRP values were recorded on 7th November, of 85.1 MW at 04:15 and 8.6 MW at 07:00.

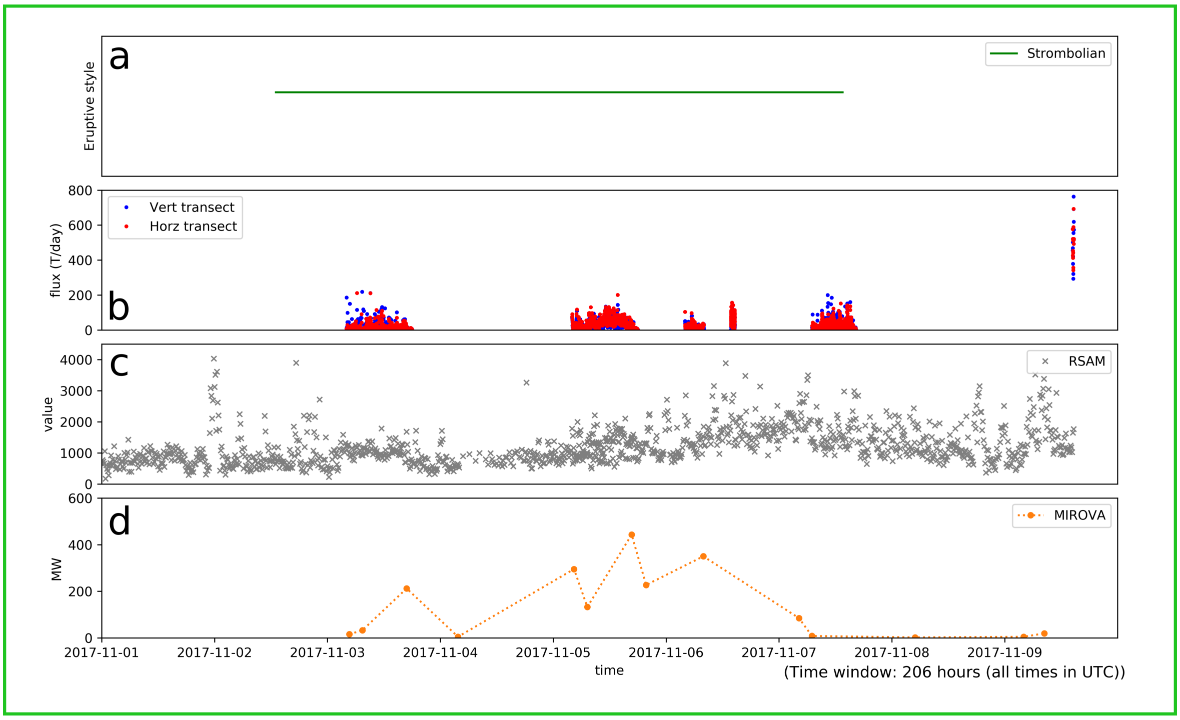


FIGURE 4.22. Multiple timeseries plot for effusive eruption beginning 5th November 2017. Top – bottom: (a) eruptive style; (b), SO_2 fluxes; (c) RSAM; (d) VRP values. Sources as from Figure 4.17.

The timescale for the November 2017 eruption can be constrained by INSIVUMEH bulletins #170-2017 and #173-2017, giving a total eruption time of 36 hours and 30 minutes. Unlike the paroxysmal eruptions described above, the November 2017 eruption does not contain a climactic period within this time window. This is illustrated by broadly consistent RSAM values. Above-background VRP values were recorded between 3rd November at 16:50 and 04:15 on 7th November, a period of 83 hours (~3.5 days). This timescale is comparable to that of the September 2016 paroxysm.

4.6.4 Results: Timescales of response

Quotations from semi-structured interviews in 2018 and 2019 provide information on timescales involved in response to eruption. They appear here in the same sequence as timelines explored in Marrero et al. [2013]: beginning with decision time, then warning time, then response time, finally evacuation time (see also Figure 4.3).

In the following quotation from fieldwork in 2019, a resident of Panimaché Uno describes the timescales involved in the decision to evacuate from a paroxysmal eruption. Their description does not isolate the decision to evacuate, but makes it clear that the decision occurred within a window of six hours, from onset of eruption at 8 o'clock at night to beginning evacuation at 2 o'clock the next morning. While the resident does not specify the date of the eruption, triangulation with other quotations suggest this was the paroxysm of 16^{th} November 2018.

> Resident of Panimaché Uno (West):
> Resident: ...that time we left at 2 in the morning, yes, because we managed to leave then.
> Interviewer: And what did the volcano look like? When you knew that you had to leave, what was the activity like?
> Resident: Ah, it was strong. It started at around 8 at night, growing stronger. It was 9, 10, and stronger, with enthusiasm, and then when we saw the blackness above, that made us afraid, that was when the COCODE brought us together. The siren sounded, and they brought us together. We got together to make the decision to leave.
> Interviewer: Then it was a decision made by everyone?
> Resident: Everyone. The COCODE asked us the question, if we wanted to leave, and we said yes.

Chapter 3 explored how communication between locals and authorities at Fuego might affect risk mitigation actions. Communication of warning messages, or "warning time", is a critical timescale explored in Marrero et al. [2013]. This timescale begins when a warning message of increasing activity is shared by officials, and ends when the exposed people have received and understood the message [Marrero et al., 2013]. Below, an official interviewed in 2018 talks about warning messages and admits that warning time is difficult to constrain at Fuego, given that warning messages often do not arrive to those communities exposed to hazards:

> Official 2:
> We make a bulletin every day, but the people - to those in the city, the bulletin may arrive, and they see it on their smartphone, on the social networks - on Twitter, on Facebook. But the people in the communities, they are the important ones. The bulletin does not reach them, because they don't have social media, they don't have internet, there is no phone signal there, so it is rather funny because [the bulletins] reach a certain population, but to those people that we are interested that it arrives, it doesn't arrive.

In an assisted evacuation, both the exposed population and authorities must prepare for evacuation. In the following quotation, an official justifies the self-evacuation policy by describing timescale of response involved in assisted evacuation and contrasting this with the disproportionately short timescale over which hazards evolve:

> Official 5:
> It would take us around two or three hours to reach each community. And the pyroclastic flows, what we learned and saw recently in the eruption of 3 June 2018, travelled from the crater to around 7 kilometres below in more or less 7 minutes.

This provides a theoretical response timescale of assisted evacuation at Fuego that can be compared with actual response timescales from previous self-evacuations. Below, a resident of San Andrés Osuna on Fuego's south flank (see Figure 3.5) speaks of the timescales involved in their community's response to the paroxysmal eruption of November 2018:

> Resident of San Andrés Osuna (East):
> Interviewer: Have you ever had to leave because of the activity?
> Resident: Yes, the other day. There was an evacuation because all the fire was coming. Was coming down. So M. [friend from community group] called us. ... it was 10 at night, or 9:30. She called the mayor, and she called the governor, and she told them, "We are leaving because we are leaving." ... The governor was coming when I called - it was 2 in the morning when [hazards] were falling here. Falling even further. And they were calling us and everything. So, "Tell the people", said the governor, "that there's an evacuation."
> Interviewer: Mm-hm.
> Resident: "You tell them, I've already done my work, and if people don't want to leave, that's not my responsibility", said the governor. And we used our whistles so that the people would leave, because there was an evacuation. The buses came. They left ... for La Rochela. There they went. Evacuating.

The final timeline explored by Marrero et al. [2013] is evacuation time. A resident of Panimaché Uno estimates the timescales involved in evacuating from their community to Santa Lucía, the ultimate destination of their community's evacuation route and the site of evacuation shelters (see Figure 4.11):

> Resident of Panimaché Uno (West):
> Interviewer: How long would it take to get to Santa Lucía from here?
> Resident: To Santa Lucía from Panimaché Uno in a vehicle, about ... slowly as the vehicles would be full ... about 40 minutes or an hour.
> Interviewer: Ah, well. And on foot?
> Resident: On foot ... I have walked before ... it took around two and a half hours.
> Interviewer: And was this in an evacuation, or ...?
> Resident: No, only for personal need ... Two and a half hours at a rather fast pace, because it is around 17 km.

This quotation provides a timeline for a complete evacuation either by vehicle or on foot. However, an evacuation may be curtailed for various reasons. Below, an official interviewed in 2019 describes how, following receipt of news of the destruction of Los Lotes in the 3rd June eruption, communities on Fuego's western flanks began evacuation but were frustrated in the process by the descent of a lahar:

> Official 1:
> Later, when they heard what had happened to Los Lotes, for example what happened in Morelia and Panimaché is that they wanted to evacuate at 4 or 4:30 in the afternoon. Because they heard the news from the other side [of Fuego]. But a lahar did not let them pass. And they had to turn back.

While broad in detail, these quotations provide some constraint on timelines of processes involved in evacuation from eruptive crisis of Fuego. The warning process, if completed in-person, appears to take several (2 - 3) hours. A similar time period is needed for response in which CONRED reaches communities, and around 2 hours is needed for evacuation from a rural community to shelters. These estimates contribute to an estimated mitigating action time (MAT) of 6 - 9 hours [Marrero et al., 2013]. While this time is relatively short, it appears to lag behind timescale of eruption. A more optimistic timescale is determined from a quotation from a resident of Panimaché Uno, who describes the evacuation of their community during the paroxysm of November 2018. This description includes an estimation for forecast, decision, warning, response, and evacuation that cumulatively took place over 8.5 hours. This is calculated from eruption onset and forecast issue at 7 o'clock in the evening to beginning of evacuation at 3:30 the following morning, adding an hour for successful evacuation to Santa Lucía by vehicle as estimated above.

> Resident of Panimaché Uno (West):
> Resident: In November 2018 it was ... the eruption began at night.
> Interviewer: At what time?
> Resident: Around 7 o'clock at night, but in the early hours it was still more intense. The people were very well co-ordinated. INSIVUMEH issued bulletins informing the emergency services of the eruption - firefighters, army, CONRED, municipalities and communities, through CONRED's UPV. A commission came in the night. They were at the INSIVUMEH observatory ...
> Interviewer: They stayed at the observatory?
> Resident: Yes ... and what they did then, around 2 in the morning, was go to all the communities in the area south-west of Fuego ... Morelia, Panimaché Uno y Dos, Santa Sofía, Yucales, Porvenir. Six communities. They went at around 2, 3 in the morning, personally informing each community leader ... it was a success. They evacuated around 3:30 in the morning towards Santa Lucía. Mostly evacuating children, women,

> older adults ... only the leaders of each household remained, as much to see what would happen as to guard the area from any individual who might ... taking advantage of the fact that there is nobody there to enter and steal, right?

4.6.5 Results: Paired timescales

4.6.5.1 September 2012 paired (purple)

The 13th September 2012 eruption was the sixth eruption of 2012. The eruption was preceded by 48 hours of elevated seismic activity including an increase in LP events and volcanic tremor, as well as production of a lava flow reaching 300 m length towards Barranca Ceniza [INSIVUMEH, 2012a]. The eruption began at 03:25 with lava flows developing in Barrancas Taniluyá and Las Lajas, which produced block avalanches that descended to vegetation [INSIVUMEH, 2012a]. Strombolian explosions generated ash plumes that at 07:15 had risen 2 km above the crater [INSIVUMEH, 2012a]; they later reached 3 km above the crater and drifted SW [Venzke, 2013]. Ash fell mostly in communities on Fuego's western flanks, including Panimaché Uno, Morelia, Santa Sofía, Sangre de Cristo, Palo Verde, San Pedro Yepocapa, and was reported in more distant cities including Mazatenango and Retalhuleu. Strombolian explosions produced degassing sounds similar to a train locomotive, and shockwaves that rattled windows and roofs of houses W and SW of Fuego. CONRED increased the Alert Level from Yellow (Prevention) to Orange (Danger). Later that morning, pyroclastic flows were produced that travelled down Barrancas Las Lajas and Ceniza: pyroclastic flows descending Barranca Las Lajas are visible in Figure 8 of Herrick, J. E. [2012], taken at 09:00 on 13th September. Descent of pyroclastic flows caused CONRED to raise the alert level to Red (Emergency) in areas SW of Fuego's summit [INSIVUMEH, 2012a]; ash generated by the eruptive plume and pyroclastic flows reduced visibility to 2-3 m in areas SW of Fuego's summit [Herrick, J. E., 2012]. Although there were plans for CONRED to evacuate 33,000 people from 17 communities [Arce and Ruiz-Goireina, 2012], in practice between 5,000 and 10,600 people self-evacuated from communities SW of Fuego: El Porvenir, Morelia, Panimaché Uno, Panimaché Dos, and Sangre de Cristo [Ferres and Escobar, 2018, Herrick, J. E., 2012]. Evacuation shelters were set up in Santa Lucia Cotzumalguapa [Venzke, 2013]. Later on the 13th, seismicity decreased as fewer pyroclastic flows were observed and explosions at the summit grew less frequent. Lava flows reached a maximum area of 1000 m length by 150 m width (Barranca Ceniza), and 700 m length by 100 m width (Barranca Las Lajas) [Venzke, 2013]. Pyroclastic flows reached 7.7 km inside Barranca Ceniza and were estimated to be an average of 25 m thickness [INSIVUMEH, 2012a]. On 14th September, CONRED reduced the alert level to Orange and local residents began to return to their homes. Interestingly, the summary report created by INSIVUMEH for this eruption contains an explicit estimate for timescale of eruptive hazards: "the generation of pyroclastic flows, which as a general rule are generated 3 - 4 hours after an eruption has started" [INSIVUMEH, 2012a]. These events are plotted on a timeline in Figure 4.23.

Because the same geophysical datasets are not available for the September 2012 paroxysm as for the 2015 - 2018 eruptive cycle, the September 2012 paroxysm could not be plotted in the same way as Figures 4.17 and 4.20 - 4.22. However, quotations from local residents provide further details of evolution of the eruption and response:

> Residents of Los Yucales (West):
> Resident One: On the 12th - 13th of September the other year it did go dark ...
> Resident Two: Ah, yes. It went dark.
> R1: They were in the school - they go on national holidays, so they were handing out medals for September 15th. That time, everything went dark. It was 11 o'clock.
> Interviewer: 11 at night?
> R1: In the morning ... And it started to thunder and thunder and the sky turned orange and black and everyone left in fear. Because of the volcano itself, you see, because of the volcano's thunder, everything went dark. Everyone left, medals or no. There they left the medals with the teacher and each one went to find their children.

> Resident of San Andrés Osuna (East):
> Resident: 2012, it was big. I was going to Escuintla when they started to call me. ... I had to return, for my daughters. And I came, and it was completely dark. At that hour [midday] it was dark.
> Interviewer: At that hour - the same day?
> Resident: A-ha. It was dark. And quite a lot of ash was falling ... but it stopped. At around ... it lasted, it lasted quite a long time, because it started at around 11 o'clock in the morning, maybe. And at, at around 4 o'clock in the afternoon it calmed down.

This final quote illustrates the timescales (and some of the confusion) involved in response to eruption:

> Resident of Panimaché Uno (West):
> Because at least for the evacuation of 13th September, I made the decision. Because on September 13th, I was not on duty. [My partner] was there. So I came with my firewood, and then I saw that the office was closed. My partner said to me, "And what are you going to do?". "What am I going to do?", I said to him, "right now I'm going to leave my firewood, and-". "No", he told me, "I'm leaving. I already sent my family," he told me, and, "I don't know what you are going to do." "Ah, I'm going to wait," I said, "Let's see what happens." "No," he told me, "I already spoke with [INSIVUMEH], and ... and I'm going." "Well, go carefully, and go," I told him. "But I will stay here." And I stayed, to open the observatory, and left my firewood over there. And I opened it, and I walked in. I called [INSIVUMEH] and said, "Here I am. Anything you need,

> we are ready." ... I stayed. And the COCODEs came, and ... how could I leave with the COCODEs coming here? As if on the run? Of course not, right. Imagine - "I can't take it,a motorcycle is good enough for me, and I'm off!" I said [to the COCODE], "No, gentlemen, let's leave." But me running away, and the COCODE here? Of course not, right? So, I stayed. About 3 hours to find out what, what my partner thought, right. Maybe he reacted suddenly. Because he was scared. And this time I suffered. I came to help. I asked him, "Why did you leave?", I said, "Because the work is here. One has to pay attention to the activity. If you can no longer avoid it, pray to the Lord and I will leave, because [the situation] is already very critical." And he said, "I can't stay here anymore. In that case, they'll know that the situation is critical. That there won't be anyone here at the observatory." "I'll get to the point," I said. "Look how it is right now, and us running away? No", I said. "That's not right." "Yes, you are right.", he said. But he had already run away. The three hours that I stayed here alone, until he thought, he reacted, he came up again. "I had to come," he told me. "It's alright," I said. But as I said, it is true, one needs courage to be in this position. One needs courage.

Figure 4.23 shows the timeline of events for the 13th September 2012 paroxysm, as constructed from the data sources above.

Timescales of response after those of Marrero et al. [2013] can be estimated for this eruption. These include AET of 5 hours and decision time (DT) of ~5 hours. The AET is calculated from when INSIVUMEH announced the beginning of eruption (04:00) until when pyroclastic flows descended (09:00). DT is the period from forecast issue (INSIVUMEH's announcement at 04:00) to when decision-makers call for evacuation (CONRED raising the alert level to Red at 09:12). The MAT and required evacuation time (RET) are more difficult to deduce, given the uncertainty of when local residents decided to evacuate and when evacuation was completed. However, from quotations above estimates can be made. The decision to evacuate Panimaché Uno was made ~3 hours after the resident quoted above received news from INSIVUMEH of the eruption. If this was roughly concurrent with CONRED's Red alert, the decision to evacuate Panimaché Uno occurred after 12:00. In Section 4.6.4 a resident estimated it took 2.5 hours to reach Santa Lucía from Panimaché Uno on foot, and confirmed that many locals evacuated this way in 2012. Some allowance must be made for residents to gather family, papers, or attend to animals. Therefore a reasonable estimate of when evacuation of Panimaché Uno was completed is ~16:00. The MAT (time period between evacuation decision is made/announced to the population and when evacuation is completed) could be interpreted as either ~7 hours (from CONRED raising alert level at 09:00 to evacuation completion at ~16:00) or ~4 hours (from locals' decision to evacuate at ~12:00 to evacuation completion at ~16:00). The RET (beginning when the forecast is announced and ending when evacuation has been completed) was 12 hours. The required evacuation time

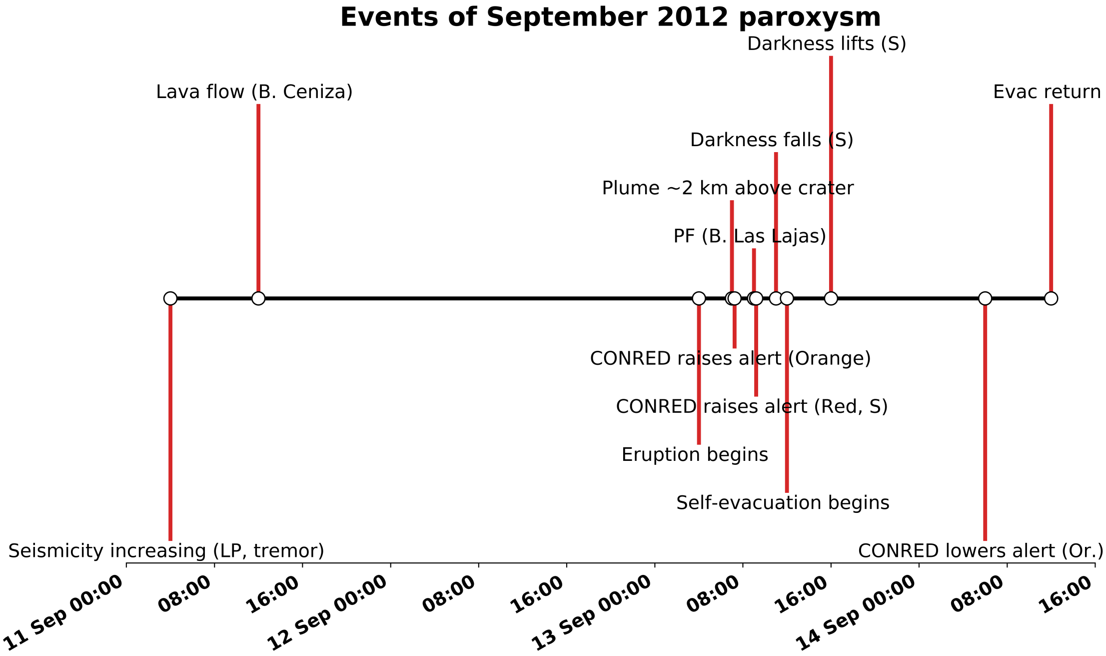


FIGURE 4.23. Timeline of events for the 13th September 2012 paroxysm, including physical hazards, locals' observations, and actions of INSIVUMEH and CONRED. Events and times recreated from sources above, including GVP, INSIVUMEH bulletins, information from semi-structured interviews, and internet articles.

includes response time (RT), or the time for residents to prepare for evacuation. It is interesting that in Chapter 3.6.2.3 several residents of Panimaché Uno stated that their response time in future eruptive crisis would be minimal given their direct experience of previous eruptions. These timescales are discussed in Section 4.7.2.

4.6.5.2 June 2018 paired (pink)

A synopsis of the 3rd June 2018 eruption appears in Section 4.6.3.3, so will not be repeated here. Descriptions of the sequence of events surrounding the eruption also appear in Ferres and Escobar [2018] and Gavin and Ltd. [2018]. Figure 4.24 gives a synopsis of events from 2nd - 3rd June 2018. Quotations from semi-structured interviews provide additional constraints on timing of events during the eruption:

> Official 4:
> We don't give orders, you understand. We give recommendations and when we were on - at approximately 12:30, we were on the bridge. We requested that it be blocked, that is, that the RN-14 route between Alotenango and Escuintla be closed. We asked the people on the bridge to get out of there. When we saw - because as I told you, it

> descended little by little. When we saw that it was closer, at approximately 2 in the afternoon then we told those in Los Lotes to leave, or to take care. But no, nobody paid us any attention. Nobody, nobody, nobody.

Here an official explains dropping a resident off at their place, and accurately timing the descent of pyroclastic flows on Los Lotes:

> Official 4:
> Official 4: When I went to drop her off, and I returned to Los Lotes, they had already started to descend.
> Interviewer: And that was what time in the afternoon?
> Official 4: At 3 in the afternoon was when they started to descend on the bridge. And I was delayed around 10 minutes in going to drop her off, and I returned to Los Lotes. And already the flow was arriving.

Figure 4.24 shows the timeline of events for the 3rd June 2018 paroxysm, as constructed from the data sources above.

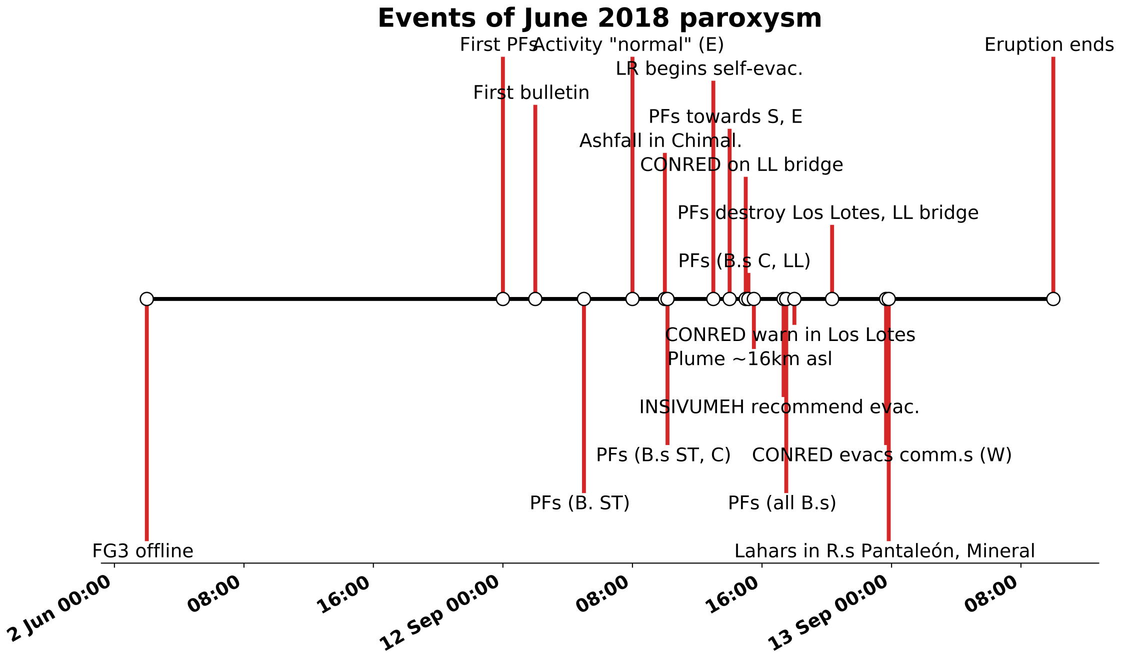


FIGURE 4.24. Timeline of events for the 3rd June 2018 paroxysm, including physical hazards, locals' observations, and actions of INSIVUMEH and CONRED. Events and times recreated from sources above, including GVP, INSIVUMEH bulletins, information from semi-structured interviews, and internet articles.

Timescales of response after those of Marrero et al. [2013] can be estimated for this eruption. Different estimates can be made depending on definition of when the forecast and event occurred: for simplicity, I will define 'forecast' as INSIVUMEH's announcement of eruption at 06:00, and 'event' as the descent of pyroclastic flows over San Miguel Los Lotes and the Las Lajas bridge at 15:10. Thus, AET was ~9 hours for Los Lotes and decision time (DT) was ~6 hours. DT began with forecast issue at 06:00 and ended with CONRED beginning the call for evacuation at ~12:00 following La Reunión's self-evacuation at ~11:30. An alternative DT of 8 hours can be obtained if using INSIVUMEH's recommendation for evacuation, given at 13:40. CONRED reported that all communities on Fuego's west flanks were evacuated by 16:50, giving a MAT for this eruption of ~5 hours (12:00 - 16:50). The RET was ~11 hours (beginning with forecast at 06:00 and ending with evacuation completion at 16:50). Several inconsistencies must be noted here. First, the response timescales presented in Marrero et al. [2013] relate to a successful evacuation. The timescales I have estimated refer to evacuation of some communities. In the tragic case of Los Lotes, these timescales do not apply. Second, Marrero et al. [2013] assume the forecast defining the beginning for most response timescales to be single and static. This was not true of 3rd June 2018, as INSIVUMEH's 06:00 reported a typical paroxysm, corresponding to initial recommendations by CONRED. Later forecasts and recommendations revised the situation, announcing an eruption of greater magnitude and danger. There is some inconsistency in event reporting. CONRED reported that all western communities were successfully evacuated at 16:50. However, a resident of these communities reported that evacuation was aborted due to descent of a lahar (see Section 4.6.4. Finally, although I have given a RET consistent with the definition of Marrero et al. [2013], evacuation needed to be completed at different times for different communities in order to successfully protect people from pyroclastic flows (e.g., at La Reunión before 12:00, at Los Lotes before 15:00). These issues are discussed in detail in Section 4.7.2.

4.6.6 Results: Spatial component

Figures 4.25 and 4.26 show the evacuation routes in Figure 4.11 superimposed on the preliminary maps of pyroclastic flow and lahar hazard around Fuego (Figures 4.9 and 4.10). As before, colours denote areas of high (red) and moderate (yellow) pyroclastic flow hazard (Figure 4.25) and areas of high (red), moderate (orange), and low (yellow) lahar hazard (Figure 4.26). Communities are labelled on the hazard maps. Orange and red evacuation routes are south towards Ingenio Pantaleon, blue evacuation route is south towards La Providencia (and onwards to Siquinalá), and yellow evacuation route is east towards El Rodeo (and onwards to Escuintla).

Figure 4.25 shows that evacuation routes for several communities around Fuego involve traversing an area of greater pyroclastic flow hazard. For residents of La Rochela, the blue evacuation route terminates in Siquinalá, well outside the pyroclastic flow hazard zone and with better resources and amenities than in rural and isolated La Rochela. However, evacuating via

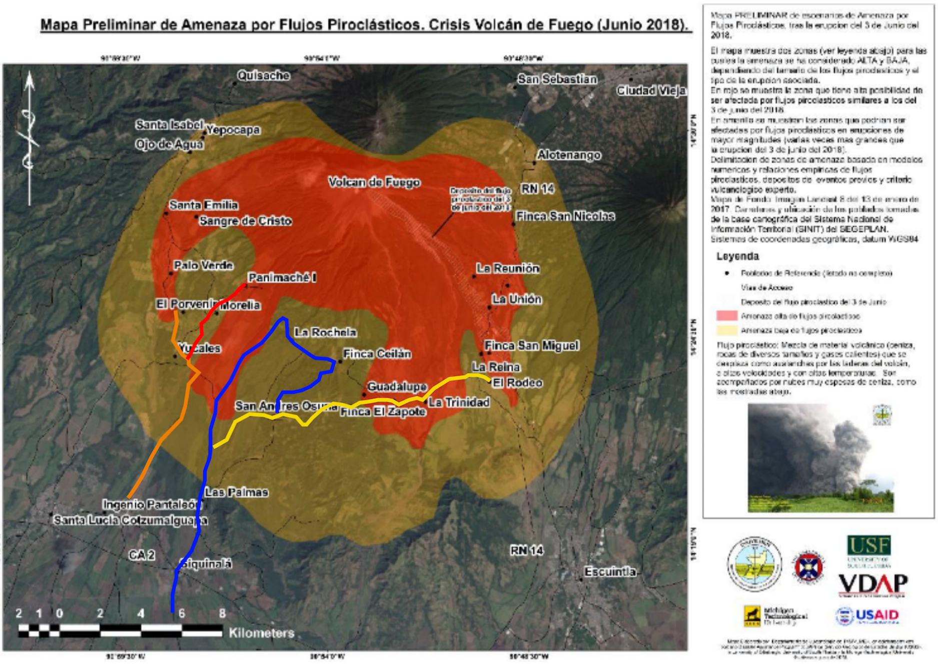
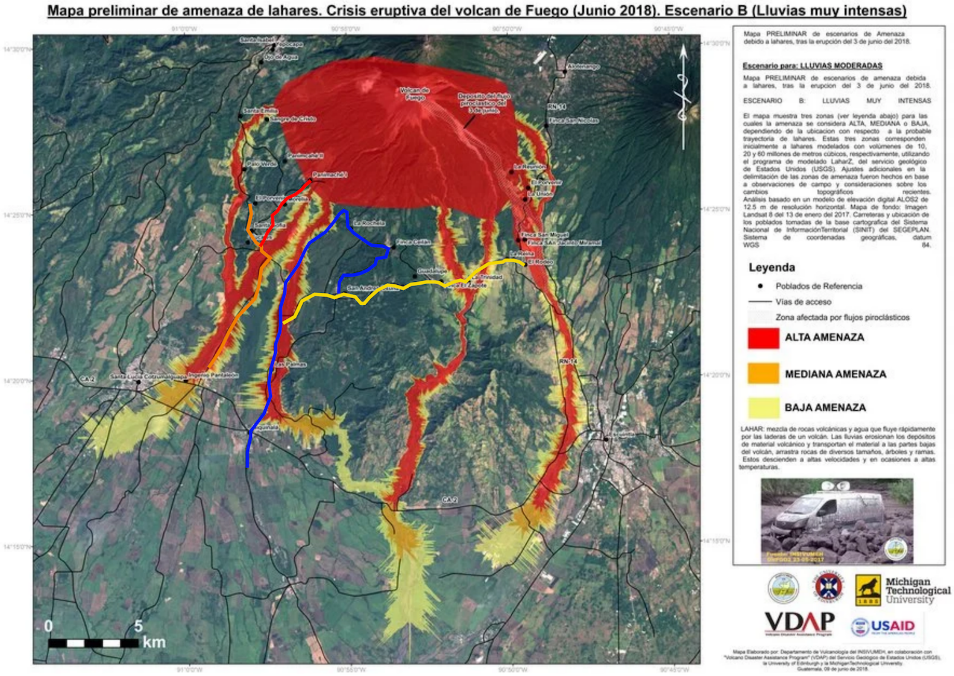


FIGURE 4.25. Evacuation routes for communities on flanks of Fuego superimposed on pyroclastic flow hazard map generated after the 3rd June eruption. Evacuation routes are those generated by CONRED in Figure 4.11.

this route involves descending the flanks of Fuego close to Barranca Ceniza for approximately 5 kilometres. Similarly, the yellow evacuation route that may be used by residents of San Andrés Osuna and those further east involves traverse of Barrancas Trinidad and El Jute. This traverse through a zone of high pyroclastic flow hazard also extends for approximately 5 kilometres and is approximately 12 kilometres from Fuego's summit, a distance to which pyroclastic flows have travelled in recent living memory [Albino et al., 2020].

Similarly, Figure 4.26 shows that many communities on the flanks of Fuego must traverse areas of greater lahar hazard when following evacuation routes to safety. Residents of Panimaché Uno and Morelia, following the red route, join those from El Porvenir and Los Yucales to continue along the orange evacuation route to Santa Lucía Cotzumalguapa. Residents evacuating along this route must pass Barranca Taniluyá, a traverse across a ravine that frequently hosts powerful and fast-moving lahars, associated with a high lahar hazard zone several hundred metres wide. Following the blue evacuation route involves attending the descent of Barranca Ceniza. Around the community of Las Palmas, this barranca is very shallow, and recent years have seen powerful lahars that have destroyed infrastructure and deposited material in the surrounding area [Naismith et al., 2019a]. Therefore the zone of high hazard is several hundred metres wide and residents must follow this for approximately 10 kilometres. Finally, the yellow evacuation route used by residents of San Andrés Osuna and those further east traverses Barrancas Trinidad, Las



Mapa PRELIMINAR de escenarios de Amenaza debido a lahares, tras la erupción del 3 de junio del 2018.

Escenario para: LLUVIAS MODERADAS

Mapa PRELIMINAR de escenarios de amenaza debida a lahares, tras la erupcion del 3 de junio del 2018.

ESCENARIO B: LLUVIAS MUY INTENSAS

El mapa muestra tres zonas (ver leyenda abajo) para las cuales la amenaza se considera ALTA, MEDIANA o BAJA, dependiendo de la ubicacion con respecto a la probable trayectoria de lahares. Estas tres zonas corresponden inicialmente a lahares modelados con volúmenes de 10, 20 y 60 millones de metros cúbicos, respectivamente, utilizando el programa de modelado LaharZ, del servicio geológico de Estados Unidos (USGS). Ajustes adicionales en la delimitación de las zonas de amenaza fueron hechos en base a observaciones de campo y consideraciones sobre los cambios topográficos recientes. Análisis basado en un modelo de elevación digital ALOS2 de 12.5 m de resolución horizontal. Mapa de fondo: Imagen Landsat 8 del 13 de enero del 2017. Carreteras y ubicación de los poblados tomadas de la base cartografica del Sistema Nacional de InformaciónTerritorial (SINIT) del SEGEPLAN. Sistema de coordenadas geográficas, datum WGS 84.

LAHAR: mezcla de rocas volcánicas y agua que fluye rápidamente por las laderas de un volcán. Las lluvias erosionan los depósitos de material volcánico y transportan el material a las partes bajas del volcán, arrastra rocas de diversos tamaños, árboles y ramas. Estos descienden a altas velocidades y en ocasiones a altas temperaturas.

Mapa Elaborado por: Departamento de Vulcanología del INSIVUMEH, en colaboración con "Volcano Disaster Assistance Program" (VDAP) del Servicio Geológico de Estados Unidos (USGS), la University of Edinburgh y la Michigan Technological University.
Guatemala, 09 de junio de 2018.

FIGURE 4.26. Evacuation routes for communities on flanks of Fuego superimposed on lahar hazard map generated after the 3rd June eruption. Evacuation routes are those generated by CONRED in Figure 4.11.

Lajas and El Jute that also accommodate powerful lahars. These lahars may be generated more frequently during the rainy season but occur throughout the year (e.g., Chapter 2.6.4 describes lahars occurring in Barranca Las Lajas in October 2020).

4.7 Discussion

This discussion section is ordered like the results, beginning with timescales of eruption (Section 4.7.1), then response (Section 4.7.2), before the two are compared to explore spatial variability and mental models of risk (Section 4.7.3). Section 4.7.1 begins by considering patterns in geophysical data (Section 4.7.1.1) and relationship between lava and pyroclastic flow hazards in recent paroxysms (Section 4.7.1.2), before evaluating in turn timescales of four individual eruptions presented in Figure 4.13 (Section 4.7.1.3). This section concludes with a discussion of uncertainties involved in eruption timescales (Section 4.7.1.4). Timescales of response in previous eruptions of Fuego are critically assessed in Section 4.7.2 to determine where response time could be reduced. Section 4.7.3 draws on timelines in the evacuation process described in Marrero et al. [2013] and mental models literature presented in Section 4.3.4 to answer the question which began this chapter: can current volcanic risk mitigation policy at Fuego provide sufficient warning time to protect local residents?

4.7.1 Discussion: Timescales of eruption

4.7.1.1 Patterns in geophysical and gas data

Chapter 2 showed the strong correlation between RSAM values and explosive paroxysmal activity in 2015 – 2018. This was confirmed by Castro-Escobar [2017] through observations in March 2014 – October 2015 of increasing RSAM values corresponding with paroxysmal onset. This correlation also occurs during the three paroxysmal eruptions in 2015 - 2018 studied in this chapter. The maximum values of RSAM vary greatly for each paroxysm (July 2016 max RSAM = 7475, September 2016 = 4910, June 2018 = 12664), therefore absolute value of RSAM does not appear to indicate paroxysm is imminent. Rather, a rapid increase in RSAM over a short timescale (~12 hours) is indicative of impending paroxysm. This can be observed in the timeseries plots of July 2016 (Figure 4.17) and September 2016 (Figure 4.20) and is absent from the effusive eruption of November 2017 (Figure 4.22). The failure of FG3 during June 2018 prevents determination of this increase (Figure 4.21). In addition, FG3 is located on an active farm (*Finca Candelaria*) and is vulnerable to farm operations: a spike in values in November 2016 (Figure 2.8(a)) was unrelated to eruptive activity and probably represented machinery operating nearby. Castro-Escobar [2017] also observed that small-scale changes in RSAM may represent either eruptive processes or work on the *finca* or on the nearby road. Nevertheless, RSAM values from FG3 prove consistent enough that an increase in RSAM above baseline levels are a reliable indicator for INSIVUMEH to anticipate future explosive paroxysms of Fuego.

Nadeau et al. [2011] related patterns in SO_2 and RSAM at Fuego in 2009, and attributed this to rapid (over minutes) sealing of the conduit through rheological stiffening before explosion. Results in this chapter do not show strong evidence for this mechanism occurring during recent eruptions. For instance, Figure 4.19 shows SO_2 fluxes and RSAM for the 4-hour climax of the July 2016 paroxysm. Over this period, SO_2 fluxes and RSAM correlate, declining slowly before a rapid increase in RSAM immediately precedes an increase in SO^2. The broad correlation between the two signals points to a relationship between generation of seismic tremor and outgassing activity at Fuego, as observed at Villarrica by Palma et al. [2008]. However, the lack of minute-scale correlations between SO_2 and RSAM as observed by Nadeau et al. [2011] suggests that the rheological stiffening mechanism is unlikely to occur in Fuego's new eruptive regime. The paroxysmal phase of eruptions in the 2015 – 2018 cycle, involving accelerating explosive activity from an open vent occurring over <24 hours, requires conditions incompatible with a blocked upper conduit.

In Section 4.4 I predicted that SO_2 flux would increase prior to paroxysmal onset. Results in Section 4.6.1 do not provide strong evidence to support this prediction. This was partly due to difficulties in data capture: there were significant instrumental and environmental impediments to consistent capture of SO_2 by NicAIR (see also Section 4.5). Frequent instances of low SO_2 fluxes during periods of high explosivity are probably underestimations due to signal obfuscation

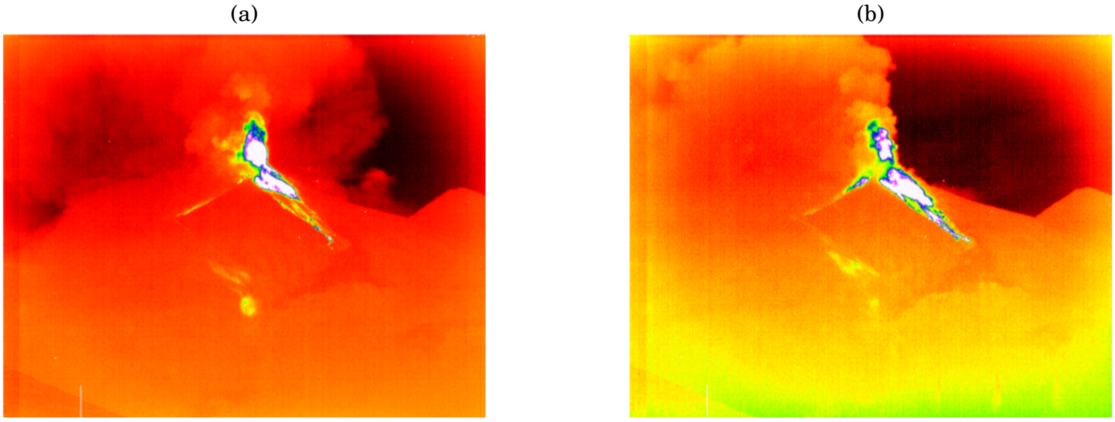


FIGURE 4.27. Comparison of broadband images on 29th July (times in UTC). (a) 9:10, flux 177 T/day. (b) 13:16, flux 774 T/day. Descent of pyroclastic flows in Barranca Ceniza seen in right-hand image (see also Figure 4.17 for image and accompanying RSAM). Note that at 12:30 UTC on 29th July, NicAIR frequency of image capture increased from 1/60 Hz to 1/12 Hz.

by ash (Figure 4.27). Conversely, overestimation of SO_2 fluxes was also common. Several days of capture show a runaway trend where fluxes increased exponentially before disappearing (see Figure 4.18 at 13:00). This is likely due to the camera overheating during hot afternoons. At these times, it is difficult to determine at what point SO_2 values cease to be valid. In future, more regular in-field calibration may help to constrain at what point NicAIR overheats and therefore when flux values should be judged as unreliable. Apparently unreliable SO_2 flux values can be explored further by evaluation on an image-by-image basis of the .fits files that are processed to create SO_2 images, although this might not explain differences in values. Figure 4.27 illustrates this by comparison between two images on 29th July 2016, during paroxysmal climax. While an ash-rich eruptive plume is present in both figures, Figure 4.27a at 09:10 gives 177 T/day, Figure 4.27b at 13:16 gives 774 T/day. The large difference resulting between two images with apparent high ashiness is unclear.

Table 4.1 presents SO_2 values for several pre-, syn-, and post-paroxysmal periods. There is scant evidence for degassing trends during Fuego's recent paroxysmal eruptions. Delle Donne et al. [2019] found strong similarities in degassing dynamics of eruptions in Etna's paroxysmal sequences of 2014 – 2016; I adopted this format for Figure 4.15. At Fuego, cumulative SO_2 degassing for each paroxysm follows a similar slope, and reaches 500 - 650 T/day around 10 days after paroxysmal onset (10 days after star in Figure 4.15). However, in contrast to strong similarities between Etna's paroxysms, paroxysms of Fuego show differences in degassing rates and day of paroxysmal onset against cumulative degassing rate (Figure 4.15). These differences support the conclusions of Castro-Escobar [2017], who proposed that Fuego's paroxysms are controlled by multiple different regimes and therefore cannot be forecast by monitoring a few parameters. Results in this chapter show only broad trends in SO_2 degassing at Fuego. Table 4.1 shows that SO_2 flux values are generally higher before paroxysm (e.g., 100 T/day on 25th July 2016). Rodríguez et al. [2004] noted an increase in SO_2 at Fuego prior to a paroxysm in February 2002, and argued that this increase could be linked to greater supply of basaltic magma, an opening of the system through fracture propagation [Edmonds et al., 2003], or both. That this chapter and Rodríguez et al. [2004] agree on pre-paroxysmal increases in SO_2 suggest the degassing mechanisms proposed by Rodríguez et al. [2004] continue to occur at Fuego in the new eruptive regime. This implies some temporal stability in Fuego's magmatic system. This chapter's results also agree with Rodríguez et al. [2004] in observing decreases in SO_2 flux after paroxysm, likely caused by lower permeability of the system. I propose that the decreased permeability of Fuego's system after paroxysmal eruption occurs because fractures are no longer forced open by the influx of SO_2 from a rising body of basaltic magma. General trends in SO_2 prior to and following paroxysm of Fuego, together with a tentative pattern in cumulative SO_2 flux reached after paroxysm, warrant future investigation at Fuego. However, the large uncertainties in these trends, coupled with SO_2 signal obfuscation by volcanic ash and processing required, mean that measurement of SO_2 fluxes is not a strong candidate for inclusion in forecasting of future paroxysmal eruptions of Fuego.

Interestingly, cumulative SO_2 output from the November 2017 effusive eruption surpasses that of any paroxysm (Figure 4.15). This is associated with a 15-minute capture on 9th November 2017 and may not be fully representative of typical passive degassing rates. However, this is an interesting observation given that previous studies estimate ~95% of Fuego's SO_2 degassing budget comes from explosive activity rather than passive degassing [Burton et al., 2015]. This would disagree with such high SO_2 output during passive degassing. The most likely interpretation is that my results significantly underestimate cumulative SO_2 output of a paroxysm because of instrumental error and plume ashiness. Unfortunately, quantification of ash levels in NicAIR images is beyond the scope of this chapter.

4.7.1.2 Relationship between hazards: lava and pyroclastic flow coincidence

While Fuego's pre-2015 paroxysms are dominated by either lava effusion or pyroclastic flow formation (Escobar Wolf [2013], pg. 30), Chapter 2 showed that both hazards feature strongly in the new eruptive regime (see Table 2.1). Table 4.2 shows that Lava flows and pyroclastic flows are strongly correlated by direction of travel. What causes this? One explanation is that pyroclastic flows are directly generated through collapse of a lava flow front. However, Fuego's block-and-ash pyroclastic flow deposits more closely resemble deposits typical of dome collapse at andesitic volcanoes [Escobar Wolf, 2013]. Evaluating pyroclastic flow volumes may determine whether lava flow front collapse is a valid formation mechanism. INSIVUMEH gives volume and length estimates of pyroclastic flow deposits in Barrancas Seca (Santa Teresa) and Honda from the 31st January 2018 paroxysm. Flow lengths and volumes were 5.79 km and 3,879,901.294 m^3 (Honda) and 4.20 km and 659,870.40 m^3 (Santa Teresa) [INSIVUMEH, 2018]. Estimates of lava flow lengths were 800 m (Honda) and 1,500 m (Santa Teresa). Assuming an average flow thickness of 5 m on steeper slopes (>20°near summit [Escobar Wolf, 2013])), and an average width of 20 m [Escobar Wolf, 2013], we obtain lava flow volumes of 80,000 m^3 (Honda) and 150,000 m^3 (Santa Teresa). Although this is a very rough estimate, the increase in lava flow volume to pyroclastic flow volume by a factor of 4–5 is improbably large - and requires that the entire length of the lava flow is available for collapse. Pyroclastic flows are therefore at least partly formed by another mechanism and from another source. This theory is supported by comparing flow compositions. While pyroclastic flows contain abundant blocks with porphyritic textures similar to Fuego's lava flows, blocks are held in a matrix of finer ash and lapilli that are created explosively [Escobar Wolf, 2013]. Therefore, correlation of flow direction requires another explanation.

A potential answer comes from the top: Fuego's summit morphology controls formation of both lava and pyroclastic flows. The process begins when persistent lava fountaining accumulates a cone of pyroclastic material in Fuego's summit crater. Gravity-driven shedding of this cone could itself trigger paroxysm (Chapter 2.6). If this shedding develops, the cone could dribble over Fuego's crater perimeter wherever elevation is particularly low. Dribble feeds lava flows that grow while shedding incandescent blocks down Fuego's flanks (the frequent avalanches observed from OVFGO1). But how could crater morphology direct pyroclastic flow formation? During paroxysm, Fuego's eruptive column is only partly successful at entraining ambient air and rising to height. This results from either low volatile content (exsolved water %), large crater diameter relative to magma discharge rate, or both (Francis & Oppenheimer (2003), pg. 180). Furthermore, discharge rate could be retarded by volume of overlying material in pyroclastic cone generated by previous fountaining activity. Fuego's eruptive column during paroxysm is dynamically collapsing i.e., producing pyroclastic flows as it rises. Summit material forced out by rising magma, too dense to rise in the eruptive column, seeks the path of least resistance: the crater depression that also provided escape for the precursory lava flow. This model of pyroclastic flow formation has also been suggested at Volcán Arenal in Costa Rica [Alvarado and Soto, 2002, Cole et al., 2005], which produced pyroclastic flow deposits that in description are strikingly similar to those of Fuego. At Arenal, lava flow formation is a more significant harbinger of pyroclastic flow formation than summit explosive activity [Cole et al., 2005]. Can this idea also answer why, at Fuego, some lava flows during paroxysm did not augur pyroclastic flow? This could simply be a lower magma supply rate. In paroxysms that did not produce pyroclastic flow, magma supply rate is either (1) not high enough to produce a summit cone with sufficient confining pressure to retard rising magma; or (2) insufficient to overpower confining pressure of the summit cone to produce pyroclastic flows. Future efforts to determine the magma supply rate at Fuego could include DEM differencing of summit morphology and SO_2 degassing over a long period.

What explains the three exceptions of Table 4.2, where syn-paroxysmal pyroclastic flows occurred in barrancas that did not receive lava flows? Given Barrancas El Jute and Las Lajas lie in the same direction (SE of summit), and the 2nd January 2016 paroxysm was preceded by a lava flow towards Las Lajas, this flow is the likely source for the El Jute pyroclastic flows also. During the latter two paroxysms, pyroclastic flows occurred in multiple directions: Santa Teresa (SW of summit), Trinidad (S), and Las Lajas. Both paroxysms are among the largest of the new eruptive regime. It is likely that in larger paroxysms, pyroclastic flow volume is sufficient to overcome confining topographies at summit.

In summary, there is a strong link between lava and pyroclastic flow direction in recent paroxysms. This observation could strengthen INSIVUMEH's efforts in communicating volcanic risk. While special bulletins contain both information on lava flow effusion and warning of increased threat of pyroclastic flow, the latter is given for all areas surrounding Fuego. From this one might infer that pyroclastic flow hazard is equally high around the volcano. This is not the case: a lava flow in Barranca Las Lajas is unlikely to augur a pyroclastic flow in Santa Teresa. This preliminary evidence of flow correlation encourages further investigation of pyroclastic flow triggering mechanism(s) (e.g., through hazard modelling studies).[6] This could improve forecasting accuracy of these destructive flows. However, even if such investigation elucidated triggering mechanisms, corollary work would need to be done to integrate any improvements in scientific understanding into forecasts and risk mitigation strategy. Based on results of Chapters 2, 3, and this chapter, I have included a list of suggestions for strengthening these areas in Chapter 5.

4.7.1.3 The four horsemen of the apocalypse: Timescales of eruption

RSAM is a reliable indicator of imminent paroxysm of Fuego, increasing sharply during the hours of acceleration towards eruptive climax (Section 4.7.1.1). However, the timescale over which RSAM forecasts paroxysm varies: from ~4 hours (July 2016 paroxysm) to ~8 hours (September 2016). Instead of a numerical value above which a paroxysm can be reliably forecast, a relative increase in RSAM over 4-8 hours is indicative of impending paroxysm. No such increase can be observed for the effusive eruption of November 2017 (Figure 4.22). Timescales for the period of acceleration towards paroxysm are critical for evaluating necessary limits on response timescales, as shown by Marrero et al. [2013]. Figure 4.28 compares timescales of eruptions for the three paroxysms in the 2015 - 2018 regime studied in this chapter.

Timescales over which eruptive hazards evolve during paroxysm vary widely at Fuego. However, an important point is that pyroclastic flows can develop at any point during a paroxysm (Figure 4.28). For instance, during the June 2018 paroxysm pyroclastic flows were reported descending Barranca Las Lajas only one hour after INSIVUMEH announced the beginning of an eruption. Further pyroclastic flows appeared days after the eruption, on 5th and 6th June. Conversely, the first pyroclastic flow of the July 2016 paroxysm appeared at 12:00, after ~4 hours of increasing seismic and effusive activity. Similarly, the first pyroclastic flows of the September

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[6] Previous research suggest they may either be produced by the "boiling-over" mechanism (see Chapter 2.2) or formed from collapse of active lava flow fronts [Lyons et al., 2010].

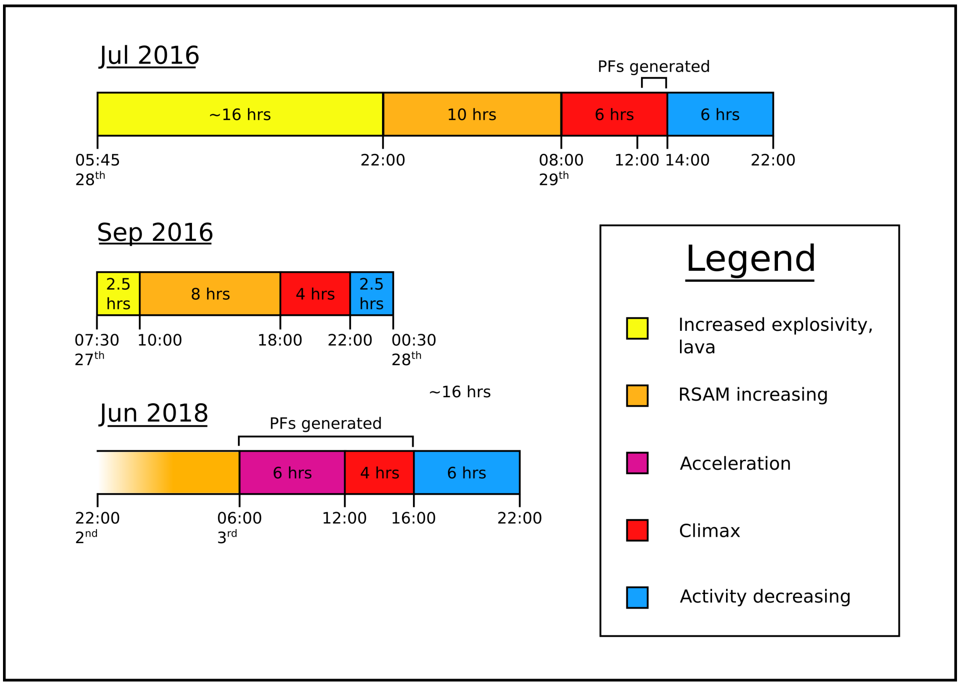

FIGURE 4.28. Timescales of eruption for three paroxysmal eruptions of Fuego in the 2015 - 2018 cycle. Note different timescales of each type of activity.

2012 paroxysm descended Fuego's flanks at ~09:00, around 6 hours after acceleration to paroxysm began with increasing lava flow effusion. This variation reiterates the many uncertainties regarding pyroclastic flow initiation mechanism(s) at Fuego discussed above. In addition, the variation urges the question of how abnormal the 3rd June 2018 eruption was in terms of magnitude and timescales of activity. Timescales of response to eruptive crisis at Fuego greatly exceed the single hour of AET in June 2018 (Section 4.6.4). If an eruption of similar magnitude occurred within the next century, risk mitigation efforts might focus on more permanent solutions such as relocation of vulnerable communities. However, the 4-8 hours of AET in September 2012 and July 2016 is closer to response timescales presented in Section 4.6.4. Future risk mitigation efforts may then focus on reducing response timescales relative to this more frequent eruption timescale. One important caveat is that the 4-8 hour eruption timescale is an upper limit, defined from the initial increase in RSAM or lava effusion to the moment of pyroclastic flow descent. However, Chapter 2.5 showed that not all episodes of lava effusion at Fuego result in paroxysm. Should warnings to evacuate be issued for each episode of lava effusion? That is impractical. In addition, the link between lava and pyroclastic flows discussed in Section 4.7.1.2 illustrates that risk is sectoral at Fuego: my estimated eruption timescale may be relevant for one flank of the volcano, but not the other. Relying on RSAM to define the beginning of eruption timescale is also problematic, because at what point does an increase in RSAM evolve from an anomalous high to a reliable indicator of eruption? A potential solution is statistical analysis of timeseries stationarity, which is discussed in the following section.

4.7.1.4 Uncertainties involved in eruption timescales

The lack of evidence for consistent thresholds in geophysical data heralding paroxysmal eruptions at Fuego, combined with the consistency with which INSIVUMEH report on paroxysm, raises an important question. How do INSIVUMEH forecast a paroxysmal eruption of Fuego? More specifically, what tools does INSIVUMEH use to forecast paroxysm, and by what criteria does INSIVUMEH determine the beginning, climax, and end of a paroxysmal eruption? While recent paroxysmal eruptions are generally associated with lava flow and increased explosive activity, as noted above there is little evidence for defining absolute thresholds in RSAM and SO^2 datasets. Furthermore, the 200 MW threshold was not employed by INSIVUMEH. During the time I was conducting the research in Chapter 2 (2017 - 18), INSIVUMEH did not include satellite imagery from MODIS in its monitoring. They did incorporate analysis of satellite imagery in their monitoring efforts, but these were secondary. In 2020 INSIVUMEH have a greatly increased budget that includes near-real-time analysis of GOES imagery, as well as infrasound analysis and data from a network of seven active seismometers (see Chapter 2.6.4). However, based on this chapter's study of recent paroxysmal eruptions, INSIVUMEH appear to anticipate a paroxysm through deterministic rather than probabilistic forecasting, using a combination of visible observations from observers at OVFGO1 and increases in RSAM. Deterministic eruption forecasting is currently employed at many volcano observatories [Pallister et al., 2019] and has historically been the favoured approach during eruptive crisis [Sparks, 2003]. However, this approach is most successful when combined with several rules of best practice Pallister et al. [2019] that are not observed in Guatemala. These include direct communication between observatories and risk management authorities and clear definition of roles of scientists and risk managers respecting mitigating actions. The lack of direct communication is illustrated in Figure 3.2 in Chapter 3, which shows the large separation between the observatory (OVFGO1) and local risk managers (UPV). A World Bank workshop following the tragedy ([BancoMundial, 2018]) acknowledges that the recommendations of Pallister et al. [2019] were not in place when the 3^{rd} June eruption occurred and urges that addressing these issues are critical for improving volcanic risk mitigation at Fuego. Unfortunately, while INSIVUMEH's monitoring capacity has significantly increased since 2018 (see Chapter 2.6.4), there is evidence to suggest that in 2021 these conditions of good communication and clearly-defined roles are still not satisfied at Fuego. These conditions are discussed in more depth in Section 4.7.2.

Uncertainty involved in knowledge of a volcano's activity appears in two forms: aleatoric (Fuego is a complex natural system) and epistemic (our knowledge of Fuego will always be incomplete) [Oberkampf, 2007]. Reducing uncertainty is often focussed on the latter, increasing our limited knowledge of a system using better data or more sophisticated interpretation of this data. This chapter and Chapter 2 attempt to reduce epistemic uncertainty of Fuego's activity by evaluating geophysical and gas parameters to determine deviations from background activity that result in an eruption requiring human response. In Section 4.7.1.1, I evaluated evidence for numerical thresholds for RSAM and SO_2 similar to the 200 MW threshold for MIROVA data presented in Chapter 2. Identifying numerical thresholds in themselves is problematic because "a numerical threshold is an expression of certainty on something we cannot be certain about" Rouwet et al. [2017]. Instead, this chapter shows that significant deviation of RSAM from baseline levels is a reliable indicator of imminent paroxysm. However, this indicator raises further issues around uncertainty. INSIVUMEH may decide a threshold value of RSAM has been exceeded, and Fuego has moved into unrest. But what if this value is a lone anomaly that does not result in eruption? INSIVUMEH's deterministic approach to forecasting has the benefit of providing a "single voice" to residents and decision-makers that encourages confidence in their advice (as reported in Chapter 3.6.2.1). However, this approach does not acknowledge the large epistemic and aleatoric uncertainties that persist for Fuego's activity. An opportunity to mitigate risk at Fuego could be the inclusion of probabilistic forecasting within INSIVUMEH's work: determination of uncertainties involved within the monitoring process through methods such as event trees may distinguish areas of greater uncertainty and trace fluctuations in uncertainty with time [Rouwet et al., 2017]. However, communication of some verbal uncertainty in INSIVUMEH's forecasts may also affect the over-reliance on their voice, with both positive and negative outcomes (as discussed in Section 3.7.2.1).

There are several other areas of research that may strengthen INSIVUMEH's monitoring efforts and improve future forecasting accuracy, and thus increase AET presented in Marrero et al. [2013]. Better instrumentation implemented since 2018 will lead to more comprehensive data coverage and eventually establish characteristic signals of various hazards, building on work such as Díaz Moreno et al. [2020]. Deeper analysis of seismic data may also improve future forecasting accuracy. Recent research has used repeating LP events to investigate processes occurring in Fuego's upper conduit Brill and Waite [2019]. LP seismicity can give a more sophisticated understanding than RSAM, which is a somewhat blunt tool. Brill and Waite [2019] and Brill et al. [2018] characterized signals from a campaign in January 2012 as the rapid pressurization of a series of connected cracks in the upper conduit. Analysis of these signals could be used to constrain volume changes in Fuego's upper conduit. They could also have direct application for hazard mitigation at Fuego and could be explored further. In another direction, statistical analysis of timeseries stationarity for various geophysical datasets could have great practical use at Fuego, elucidating apparent trends in data to aid forecasting efforts. This approach could trace temporal fluctuations in activity and related uncertainty as discussed above in introduction of probabilistic forecasting.

4.7.2 Discussion: Timescales of response

The timescales of response to a volcanic eruption may be affected by factors including (1) communication failures between different authorities [Macías et al., 1997]; (2) differences in perception of hazard by different stakeholders e.g., locals and authorities [Tobin and Whiteford, 2002]; (3) breakdown of telecommunication systems [Voight, 1990]; (4) lack of an emergency plan, or inadequate plan [Lechner and Rouleau, 2019]. Chapter 3 showed that many of these factors are present at Fuego and must be considered in future evacuation efforts. Quotations from Section 4.6.4 estimate that following decision, 6-9 hours are required to successfully evacuate from eruptive crisis of Fuego. This is an approximate estimate because of the large number of uncertainties involved. Uncertainties in response timescales cited by various stakeholders include the time taken for warning messages to arrive to communities at risk, the time taken to gather a community and collectively decide to evacuate, and the time taken for CONRED vehicles to arrive to at-risk communities. In addition, the situation where residents of Panimaché Uno prepared to evacuate but turned back from a lahar raises concern about how often such an event might occur at Fuego, and its consequences. The decision, gathering of resources, and movement required in self-evacuation is a complex and demanding task. The effect of undertaking such a task only to be thwarted during evacuation has not been considered in affecting people's experiences of evacuation has not been explored at Fuego but may be a key indicator of willingness to evacuate in future crisis.

These considerations are critical to future success of risk mitigation at Fuego. However, although INSIVUMEH's monitoring capacity has increased since 2018, thus potentially reducing epistemic uncertainty, there is little evidence that this increase has been integrated with risk mitigation policy. An effective forecast must be released to provide enough time for all evacuation steps before the most destructive period of eruption begins [Marrero et al., 2013]. Ideally, increased monitoring capacity would reduce forecasting uncertainty so that effective warning messages can be released earlier, making more time available to evacuate. However, the increase in monitoring capacity in Chapter 2.6.4 has not been tied to eruption mechanisms or integrated with hazard thresholds above which action must be taken (e.g., pyroclastic flows descending beyond a certain distance in a barranca - this latter idea recommended in the post-disaster World Bank workshop BancoMundial [2018]). In this chapter's introduction, I referenced the UNDRO-USGS risk management scheme by Macías and Aguirre [2006] that contained several assumptions about a volcano, including local awareness of volcanic hazards, presence of laws allowing protective measures to be taken, sufficient scientific knowledge to construct alternative scenarios, and possibility of disseminating warning messages with sufficient time to take protective action. I stated that there was insufficient information to say whether these conditions were satisfied at Fuego. Findings from Chapters 2 - 4 show that some of these conditions are not satisfied. Significant scientific knowledge of Fuego exists, but this has not explicitly been tied to construction of alternative scenarios or probabilistic event forecasting [Anderson and

Segall, 2013] to explore ways an eruption might evolve. Inconsistent trust in authorities (Chapter 3.7.2.1) and difficulties in delivering warning messages (Sections 4.6.4 and 4.7.3) suggest there is insufficient time to take protective action. Finally, although locals are knowledgeable of Fuego's hazards 3.7.1.3, it is uncertain how long knowledge of pyroclastic flow hazard may be preserved.

The quotations in Section 4.6.4 raise the interesting question of how knowledge of volcanic hazards is kept alive during periods of quiescence. This knowledge is important at Fuego, which has previously shown decades-long pauses between eruptive pulses [Martin and Rose, 1981]. One factor is culture, including the coincidence of an eruption with a culturally significant event or phenomenon. Local residents shared vivid memories of the 13th September 2012 eruption which occurred during celebrations for Guatemala's Independence Day on 15th September. This coincidence may have sustained collective memory of key details about the eruption, including its duration, environmental changes, and the nature of hazards during this time. In addition, local residents clearly recalled their responses and how long it took to enact them. These collective memories may be useful if a similar eruption occurred in future, as younger residents would not have the lived experience to assess whether the volcano was becoming dangerous. In this case, collective memory of previous eruptions could incite residents to evacuate before history is repeated. However, as seen in interviews with older residents in Chapter 3.6.1.2, knowledge of hazards may be preserved during quiescence - older locals described the eruptions of 1967 and 1974 in exceptional detail - but this does not appear to increase the likelihood of evacuation from eruption. Knowledge does increase the intention to evacuate Johnston et al. [1999], and regardless of evacuation can provide experience of how to protect lives and assets from these volcanic hazards. If culture plays a role in keeping knowledge of eruptions alive during quiescence, then an area of promise would be associating eruptions with culture at Fuego; through storytelling, for instance. Such associations have generated rich culture at other volcanoes and preserved knowledge of previous eruptions, both those more recent (e.g., Mt. Sinabung, Indonesia [Mori et al., 2019]) and those in the more distant past (e.g., Mt. Tarawera, New Zealand [Cashman and Cronin, 2008]). Including a cultural aspect in disaster risk mitigation welcomes the priorities and knowledge of local residents [Mercer et al., 2010] and acknowledges them as having agency and as rightful partners in guiding, not solely following, risk mitigation policy [Maldonado, 2016].

4.7.3 Discussion: Paired timescales

In this chapter's background, I quoted Fournier d'Albe [1979] who stated that effective volcanic risk management requires prediction occur on time intervals comparable with human response. Is this the case at Fuego?

In theory, yes. Figure 4.28 shows timescales of eruption for several paroxysms. Depending on when the response decision is taken, evacuation may be completed before the event (i.e., pyroclastic flow descent) occurs. For the eruptions illustrated, that decision should be made at some point near the beginning of the period when RSAM is increasing, to allow the ~9 hours required to complete evacuation estimated from quotations in Section 4.6.4. However, this time estimate is an absolute minimum. Section 4.7.2 cites many factors that complicates the response decision and extend response time. The resident of Panimaché Uno quoted at the end of Section 4.7.2 describes the evacuation in November 2018, where the warning period began at 02:00, 7 hours after eruption began. At Fuego the decision to evacuate is more typically made towards the end period of RSAM increasing, or even during eruptive climax (Figure 4.28) and therefore does not provide sufficient time evacuation to be completed before pyroclastic flows descend. Figures 4.29 and 4.30 show paired timescales for the 2012 and 2018 paroyxsms.

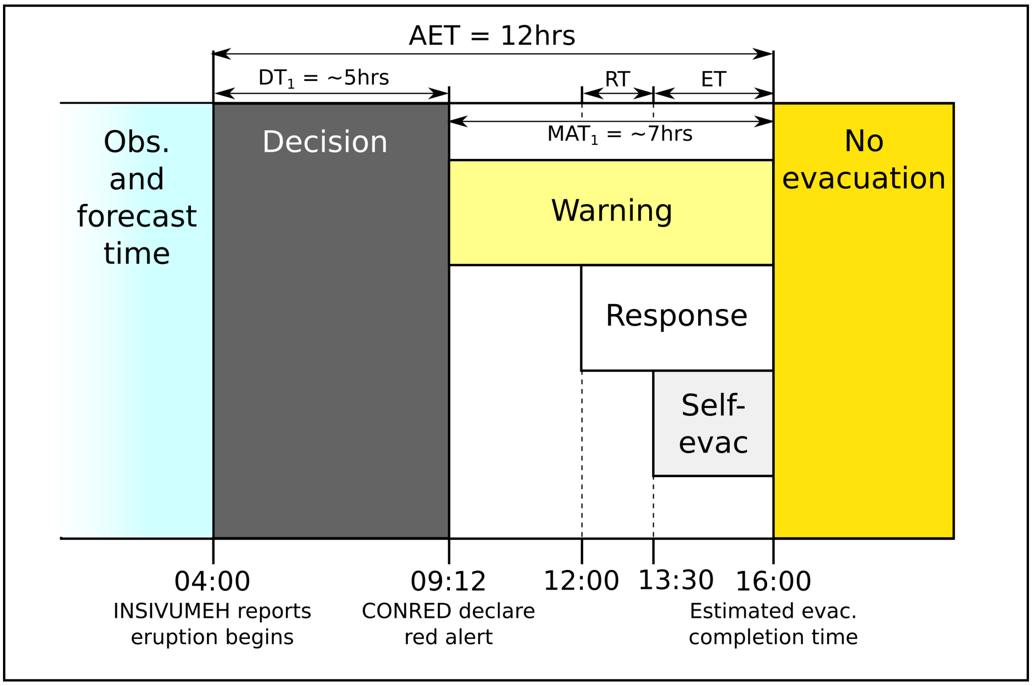

FIGURE 4.29. Comparing timescales of eruption and response for the September 2012 paroxysm. Created after Marrero et al. [2013].

While quotations in Section 4.7.2 allow estimation of theoretical response timescales at Fuego, Figures 4.29 and 4.30 allow critical analysis of previous evacuations. Such criticism is crucial, not to cast blame, but to identify how volcanic risk management can be strengthened in future.

The principal areas where response timescales are prolonged (and consequently impede effective risk management) are (1) decision time, and (2) warning time. For the September 2012 and June 2018 paroxysms, considerable time passed between INSIVUMEH's forecast and CONRED's evacuation order (5-6 hours). Such lengthy decision times may be associated with either forecast uncertainty or the complexity of decision-making at Fuego. INSIVUMEH's deterministic approach to forecasting appears to present a "single voice" (Section 4.7.1.4). However, INSIVUMEH forecasts announcing eruption report probability of pyroclastic flows in verbal terms that may be

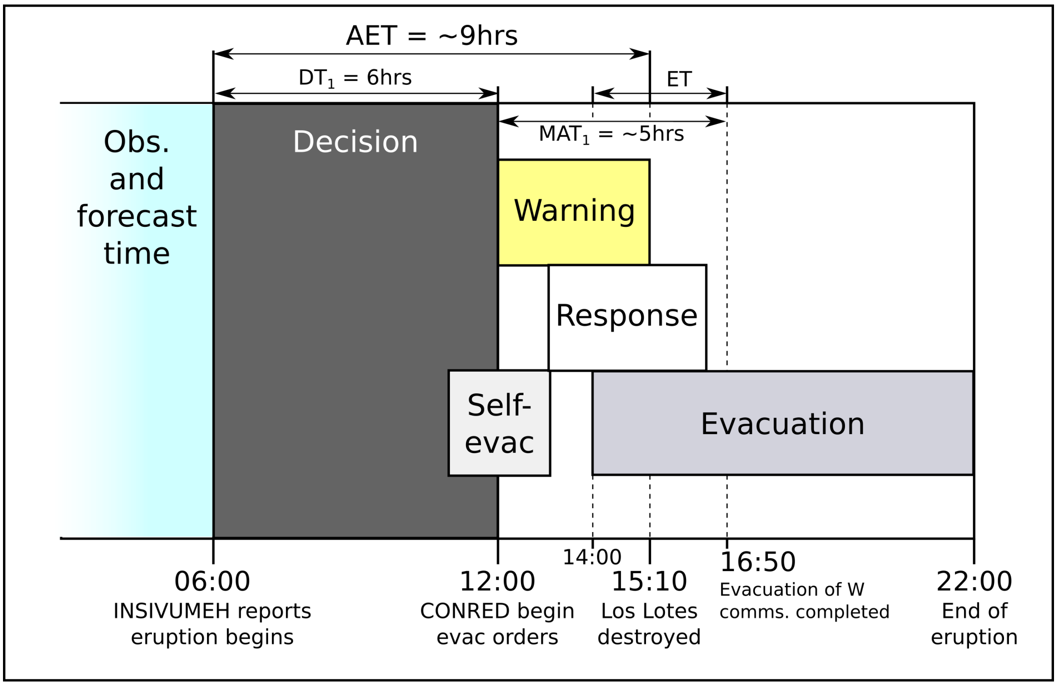

FIGURE 4.30. Comparing timescales of eruption and response for the June 2018 paroxysm. Created after Marrero et al. [2013].

misinterpreted by recipients, either by underestimating this probability or by expecting the event towards the end of an eruption [Doyle et al., 2014]. This appears to be exactly what happens at Fuego, which results in either no evacuation and no crisis (if pyroclastic flows are not generated) or belated evacuation and major crisis (if pyroclastic flows are generated). The latter occurred in both 2012 and 2018, when CONRED issued evacuation orders once pyroclastic flows began. In 2018, the 6 hours of decision time involved multiple appraisals of the situation and search for more information, as seen in Figure 4.5. Figure 4.28 shows that flows often correlate with eruptive climax; deciding to evacuate at this point is too late to ensure sufficient time to evacuate successfully. The decision-making process at Fuego also prolongs decision time. As discussed in Chapter 3.3, decision to evacuate is a complex process involving a community's COCODE and local residents. Although the resident quoted on page 148 states that this process works well in Panimaché Uno, that community has several advantages not held by others around Fuego: (1) Panimaché Uno has a small population, allowing residents to gather relatively quickly to make a decision; (2) residents of Panimaché Uno have previous experience of successful evacuation in 2012, which can positively influence evacuation [Morss et al., 2016]. The implications of this have been discussed in Chapter 3.7.2.1. Another factor for consideration is that a community's COCODE changes every few years. Even in the case of Panimaché Uno, with the trust developed from its favourable experience of community-led evacuation, can that trust be preserved through political changes? This question relates to the difficulty of keeping knowledge alive during quiescence discussed in Section 4.7.2. The resident quoted on page 150 recalls that if a decision is made to evacuate, it can be enacted quickly. To allow sufficient evacuation time, that decision must be taken much earlier than when pyroclastic flows descend, which is what currently dictates evacuation decisions. It is not clear that the decision to evacuate will be made earlier in future eruptions of Fuego. Impediments to early decision-making (including situational barriers and household characteristics) are discussed below in terms of mental models of risk.

Calculating the optimal warning time during eruption is important at Fuego, where the at-risk population is dispersed widely over remote terrain [Marrero et al., 2013]. However, warning time is poorly constrained at Fuego because influencing factors (e.g., message content, media used to send message, time of day/night) are either highly variable or poorly understood. Furthermore, the official quoted on page 148 shows that warning time is difficult to constrain because many of the at-risk population does not receive it. The proportion of population that does not receive the warning message could be reduced by receiving a warning in person, as described by the official quoted in 150. Given that authority presence in a community builds trust (Chapter 3), and trust may increase compliance with evacuation orders (Wachinger et al. [2013]), giving warning in this way may increase the likelihood of evacuation. However, it is antithetical to CONRED's stated desire to avoid delivering more people to zones of high risk. Generally, warning messages have greatest reach when delivered through a variety of methods Fearnley et al. [2017]. Volcanic risk at Fuego might usefully be mitigated by research that identifies who has access to communication, and of what kind. This might consist of surveys of population numbers that have access to phone signal, television, or internet. The benefits and challenges of using radio to communicate volcanic risk have been discussed in Chapter 2.

Response timescales at Fuego must also be considered with regard to spatial variability. Donovan et al. [2012b] found resistance to evacuation varied considerably over a small area at Merapi. This is seen at Fuego, for instance in the disparate responses of Los Lotes and La Reunión in the June 2018 paroxysm. Chapter 2 explained this disparity through unequal access to resources between the communities. Media also cited unequal access to information from authorities, and blamed CONRED for failing to warn residents and even discouraging residents from evacuating [Tobar, 2018b]. This appears to contradict the official quoted on page 154. There is likely truth in both accounts: CONRED does not assume full responsibility for calling evacuation, as the official explicitly states; however, prior to 2018 residents of Fuego may have normalized eruptions Graves [2007]. Spatial variability in response to risk appears to be linked to communication with authorities and previous success in evacuation; when these are greater, so is the desire to evacuate (Panimaché Uno, Sangre de Cristo, La Reunión). Future efforts to mitigate risk at Fuego might focus on how these communities can share their experiences with neighbours to encourage similar behaviour. Spatial variability in response must be considered against spatial variability in risk from natural hazards, which is illustrated in Figures 4.25 and 4.26. Following each evacuation route involves traversing an area of greater pyroclastic flow or lahar hazard, which residents are knowledgeable of (Chapter 3.7.1.3). However, I have previously discussed that hazards produced during paroxysm may be directed by summit morphology (Section 4.7.1.2. Therefore, a paroxysm may generate hazards that produce higher risk for people following one evacuation route and not another. But is this spatial variability included in local residents' mental models of volcanic risk?

Mental models can be used to explore how different groups of people view volcanic risk at Fuego. An important point raised by Doyle et al. [2014] is that scientists' and risk managers' mental models of risk (e.g., how they understand likelihood of pyroclastic flow descent within a time window) are inconsistent, with non-scientists often estimating an event will happen towards the end of the time window. This appears to describe the situation at Fuego, where CONRED often issue warnings relatively close to climax. Another fascinating discovery is that non-scientists appear to underestimate event likelihood when verbal terms are used, with significant effects on decision-making [Doyle et al., 2014]. As such, efforts to improve risk mitigation at Fuego should include critical analysis of the content of INSIVUMEH's forecasts and warning messages. This external information is critical in the decision-making process [Lazo et al., 2015],and it is crucial to understand how this information is interpreted by decision-makers [Donovan, 2019]. Given the self-evacuation policy at Fuego, both CONRED and local residents are decision-makers. Analysis of how decision-makers interpret warning messages thus has an additional layer of complexity, as this can mean either (1) CONRED receiving information from INSIVUMEH; (2) residents receiving information from INSIVUMEH; (3) residents receiving information from CONRED. The official quoted on page 154 shared their frustration when they shared the warning message in Los Lotes but people refused to evacuate. But did their message fall on deaf ears, or were those ears simply tuned to a different language? Conversely, the eruption of November 2018 provoked CONRED into sharing warning messages with community leaders; this time, their message was received in the manner intended (quotation page 150-151). But, as discussed in Chapter 3.7.2.3, how much of that success was in the method of delivery or message content, and how much was driven by heightened situational motivation due to recent memories of the fatal June 2018 eruption? We do not know. Based on previous mental models research, fruitful future risk mitigation efforts at Fuego could involve: (for INSIVUMEH) include probabilities in forecasts, and give forecasts over a range of time windows [Doyle et al., 2014]; (for CONRED) geographically target messages of evacuation [Morss et al., 2016]; (for residents) research media through which residents locals receive warning messages, and then strengthen those networks [Christie et al., 2015]; and encourage development of an evacuation plan that prioritizes familial safety [Lazo et al., 2015].

Figure 4.5 illustrates a mental model of information appraisal and decision-making from Lazo et al. [2015]. Although created for hurricane risk, the model is relevant to Fuego because it is iterative: in previous eruptions the decision to evacuate has taken hours as forecasts and warning messages change and costs and benefits of evacuation are weighted by different stakeholders

(Figures 4.29 and 4.30). Discussion of elements of Figure 4.5 appear throughout this thesis, including external information such as event development and behaviour (Chapter 2.6), event forecasts (Sections 4.7.1.1 and 4.7.1.3), and warning messages (above paragraphs). I have only briefly considered household characteristics through demographic information of local residents (Chapter 3); Aleyda Xiomara León Ramírez Carné [2012] provides a more comprehensive analysis of household characteristics contributing to vulnerability at Fuego, and it would be valuable reproducing this 2012 study to evaluate whether the situation has changed. Situational barriers to evacuation discussed in this thesis include "push" and "pull" factors discussed in Chapter 3.7.2.2, difficulty in enacting evacuation by foot (see quotation on page 149, and the potential for evacuation failure as illustrated by Figures 4.25 and 4.26 and the official quoted on page 150. Situational motivations may include direct severe experience of previous events. As discussed above and in Chapter 3.7.2.3, collective memory of the fatal June 2018 paroxysm may motivate evacuation. But given evidence that locals began to normalize Fuego's behaviour only months after this eruption (Chapter 3.6.1.1), it is unlikely that without additional efforts to sustain memory of the event such as oral tradition, hazard maps, or media [Fearnley et al., 2017] this experience will continue to influence local residents' mental models for response to future eruptions of Fuego.

Ultimately, this thesis suggests many situational barriers that inhibit evacuation at Fuego. If Figure 4.5 is correct that an alternative action to evacuation is often to seek more information, then we must consider the quality and availability of information available. The mental models research explored in this chapter emphasizes the necessity of risk information being tailored to specific risk and decision situations (e.g., Doyle et al. [2014], Lazo et al. [2015], Eiser et al. [2012]. However, this chapter notes that INSIVUMEH forecasts and CONRED orders are often generic, despite the high spatial and temporal variability of experience of past eruptions and exposure to volcanic hazards. I urge consideration of spatial and temporal context in future research at Fuego. Future avenues of research could include: how information from INSIVUMEH is received and interpreted outside of the scientific sphere, how situational motivations for local residents evacuating from eruption vary temporally and spatially, how collective memories of previous eruptions may be preserved during volcanic quiescence, and how INSIVUMEH's improved monitoring capacity may be translated to message creation and warning dissemination with greater temporal and spatial nuance. These are all research questions that "multiple disciplines and stakeholder communities can embrace, and in which different methodologies can pursue relevant information of different qualitative-quantitative natures across time/space/organizational scales" - the ultimate goal of both Oliver-Smith et al. [2016] and this thesis, which seeks to integrate knowledge of both physical hazards and human processes at Volcán de Fuego to present a case study that is more than the sum of its parts.

4.8 Conclusions

This chapter closes the data portion of this thesis by investigating timescales of eruption and response associated with recent paroxysmal eruptions of Fuego. Through interpretation of geophysical and gas timeseries data, we find that RSAM shows consistent patterns that may be used to anticipate imminent eruptive activity. Just as Chapter 2 showed lava effusion is likely to precede paroxysm, this chapter illustrates that a sharp increase in RSAM often augurs an acceleration to paroxysm; this increase is absent from the November 2017 effusive eruption. Exploring different models of triggering paroxysm suggest November 2017 is a "stalled" paroxysm, where the energy of the system was not sufficient to cross the threshold into a fully-fledged paroxysmal eruption.

Timescales of eruption were also explored through SO_2 timeseries and correlation of lava and pyroclastic flow hazards. SO_2 timeseries did not show significant patterns that could be used to forecast future eruptions of Fuego. Both cloud cover and technical issues impeded NicAIR's ability to capture data comprehensively. In practise, NicAIR data analysis is computationally intensive, and instrument operation is complicated by the lack of a comprehensive instruction manual or GUI available in Spanish. While gas monitoring is therefore poorly suited to INSIVUMEH's forecasting efforts, capture of gas timeseries could inform understanding of triggering processes of paroxysm that inform understanding and reduce epistemic uncertainty.

In this chapter, I elaborated on the link between lava flow effusion and other hazards that I first identified in Chapter 2. Of the paroxysms that produced pyroclastic flows in 2015 – 2018, there is a remarkably clear correlation between the barrancas towards which lava flows travelled, and those where pyroclastic flows descended. Incomplete satellite coverage and INSIVUMEH reporting can explain situations when pyroclastic flow occurred in barrancas towards which lava was not directed. The clear link between lava flow and pyroclastic flow hints at pyroclastic flows forming directly from lava flow front collapse. Alternatively, changes summit crater morphology could explain the correlation. This relationship considerably increases spatial variability in risk at Fuego, which is explored in this chapter in the context of response timescales.

Evaluation of previous eruptions at Fuego reveal that while in theory prediction and response occur over similar timescales, in practice response lags behind due to long periods of decision-making and warning. A mitigating action time of ~9 hours is estimated at Fuego. If this began towards the beginning of an eruption, evacuation could confidently be realized before pyroclastic flow descent. Instead, evacuations at Fuego are consistently decided and undertaken near eruptive climax, when local residents are at immediate risk from volcanic hazards. These findings are consistent with Chapter 3. However, while the previous chapter explored local residents' decision to evacuate, this chapter shows that authority decisions to evacuate are also made too late. Mental models research provides some answers as to why: warning messages are not interpreted as desired, forecasting uncertainties are understood in different ways, and situational barriers act to inhibit evacuation until it is absolutely necessary. The actual volcanic risk mitigation situation at Fuego is very different to the policy of evacuation "in the spirit of prevention" encouraged by CONRED. More optimistically, mental models research also provides solutions to this situation focussed on spatial and temporal contextualization of risk. This nuanced approach encourages integration of multiple methodologies that has been the guiding force of this thesis. It is also gaining popularity in the wider world of disaster research, as we shall see in the next chapter.

CHAPTER 5

CONCLUSIONS

This chapter closes the thesis with reflections on my work and its position among existing research. Given the complexity involved in undertaking an interdisciplinary project, it is helpful to begin by placing my research within the wider setting of volcanological research in 2020. This setting includes new opportunities and challenges associated with emerging interdisciplinary efforts. This is followed by Section 5.2, which reviews the objectives of this research - presented in Chapter 1 - and how they were met. This chapter, and the thesis, conclude by considering the world of volcanic risk beyond Volcán de Fuego. The transferability of this case study to an environment other than Fuego is considered, before questioning how findings from volcanic risk research can be implemented successfully into policy in a world increasingly complicated by anthropogenic climate change.

5.1 The story so far: research state-of-play in 2020

In this thesis's introduction, I stated that global disasters appear to be escalating. Human response to these disasters through research is also accelerating. Natural hazards research has greatly evolved from early work that focussed on identifying adjustments to the natural environment to minimize loss [White, 1945]. In general, research since the 1970s has moved away from the perspective that nature holds the initiative in creating calamity, and towards a perspective that promotes existing socio-economic conditions as the principal cause of disaster and the key to understanding why natural hazards may impact a vulnerable population (e.g., Hewitt [1983]; Blaikie et al. [2005]). In this perspective, disasters are not 'extreme events' representing a deviation from normality but instead an increase of everyday difficulties faced by people who are vulnerable both geographically (by living in hazard-prone areas) and socially (e.g., because of poverty) [Gaillard, 2007]. The concept of “vulnerability” is explored thoroughly in this latter perspective, and can be defined as “the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard” [UNISDR, 2011]. Vulnerability also varies according to the nature of the hazard (volcanic eruption, flood, earthquake) [Blaikie et al., 2005]. While large volcanic eruptions are relatively infrequent compared to other hazards, they can cause loss of life, livelihood, and major social disruption [Brown et al., 2017].

The beginning of the 21st century was also the advent of interdisciplinarity in volcanological research. To gain a holistic understanding of disaster caused by natural hazards, it is essential *both* to understand and quantify those hazards *and* to evaluate the ‘disaster’ of everyday life by exploring existing socio-economic conditions. Because researchers are increasingly willing to acknowledge this duality – welcoming both socio-economic conditions and natural hazards as critical in creating disaster – there has been an explosion of interdisciplinary volcanic research within the last 20 years. A good illustration of this is the special issue of JVGR in May 2008 called, “Volcanic risk perception and beyond”, which united a number of papers cited in this thesis. Many of these papers united multiple approaches to volcanic risk perception research. In the 12 years since, using multiple methods to explore volcanic risk has grown more popular. Recent successful interdisciplinary collaborations include Armijos et al. [2017] and Barclay et al. [2019].

Despite its increasing popularity in literature, interdisciplinary volcanological research continues to face problems in practice. One reason for this is the difficulty of incorporating two opposing philosophies of knowledge, the first of natural scientists (who predominantly take a positivist philosophical approach to knowledge) and the second of social scientists, who may subscribe to alternative philosophies such as constructivism [Donovan, 2019]. Holding multiple philosophical approaches is an uncomfortable aspect of interdisciplinary research. Yet, as UNISDR recently reports, it is a necessary discomfort – now more than ever:

> Current approaches to risk measurement and management are inadequate to meet the challenges of the multi-faceted interconnectedness of hazard, the barely understood breadth of exposure, and the profound detail of vulnerability; this inadequacy must be addressed if we are to ever do more than simply treat the symptoms. ... The era of hazard-by-hazard risk reduction is over; present and future approaches to managing risk require an understanding of the systemic nature of risk.

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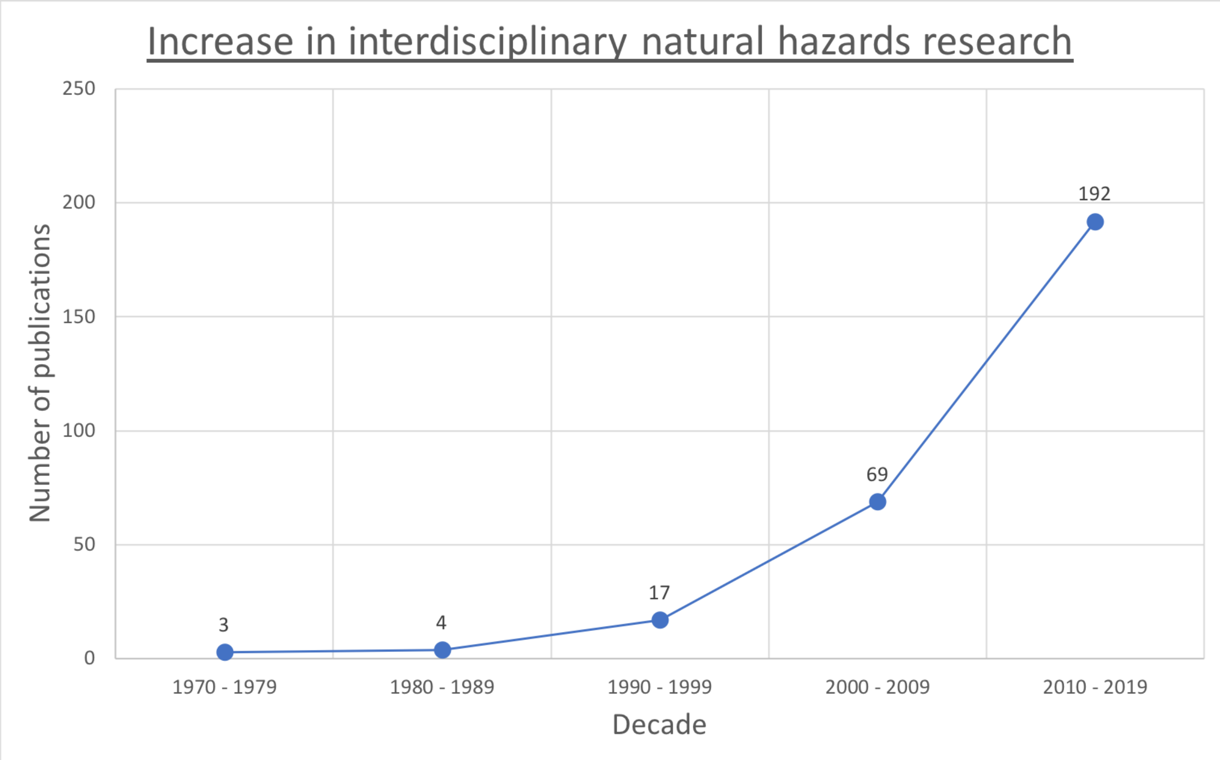

FIGURE 5.1. Increase in number of peer-reviewed articles/books/conference proceedings with 'interdisciplinary' and 'natural hazard' in previous decades. Data from `www.scopus.com`.

5.2 My book in the library: situating this thesis in the context above

The above section promotes the "necessary discomfort" of doing interdisciplinary volcanological research. This section explores how my thesis contributes to the debate by exploring my results for the nine primary research goals of this thesis, as presented in Chapter 1. Table 5.1 summarizes the goals together with where readers can find evidence of their attainment. Inspired by the thesis of Hicks [2012], I have divided my goals into two different disciplinary categories to assist evaluation.

Of the nine primary goals of this thesis, four were within physical science:

- Characterizing the recent (1999 – 2018) eruptive activity of Fuego, particularly of its paroxysms, through satellite remote sensing data;
- Discussing models that explain the sudden change in eruptive activity beginning in 2015;

- Determining, through analysis of geophysical data, timescales associated with paroxysmal eruption in the new (since 2015) eruptive regime;
- Exploring timescales associated with response to recent eruptions;

Two were within social science:

- Investigating experiences of residents of communities near Fuego of (1) previous eruptive activity and volcanic hazards, and (2) their responses to the same;
- Evaluating how experience of and response to eruptive activity influence the success of current volcanic risk mitigation policy;

Three were interdisciplinary, combining physical and social science methods and data:

- Comparing results from remote sensing data with peoples' experiences to understand how different perspectives influence volcanic risk at Fuego;
- Exploring, by comparing the timescales above, the likelihood of current volcanic risk mitigation policy at Fuego providing sufficient warning to protect lives of local residents;
- Finally, from answers to the goals above, considering (1) implications for the continued risk to lives and livelihoods of local residents from eruptive hazards associated with explosive paroxysms of Volcán de Fuego, and (2) opportunities to mitigate this risk.

This thesis was inspired by previous interdisciplinary volcanological theses such as Donovan [2010], Hicks [2012], and Delle Donne et al. [2019]. Hicks (2012) states that because her thesis was conceived as an interdisciplinary project, all of her research objectives could be assimilated into a single overarching goal: "All of these components, although themselves interdisciplinary (in that they informed one another), were integrated into an overarching interdisciplinary endeavour." [Hicks, 2012]. While each of my research chapters informed the others (and in this sense my thesis is also interdisciplinary), my approach to acquiring knowledge has evolved across my research chapters and throughout the course of this project. I began with a belief that knowledge acquisition can be objective and value-free, and evolved towards an understanding that knowledge is laden with value and influenced by my approach to my research world (see Section 1.2.1 for philosophical framework). In this sense my thesis displays some of the tensions between physical and social scientists engaging in interdisciplinary research discussed above.

Table 5.1 displays my nine primary research objectives and provides directions for the reader wishing to find a detailed explanation of each. The table is followed by an explanation of how each objective was identified and answered. This section concludes with a summary of the thesis's limitations and contributions.

	Objectives	**Evidence**
1	To characterize the recent (1999 - 2018) eruptive activity of Fuego, particularly of its paroxysms, through satellite remote sensing data and other datasets	**Chapter Two**
2	To discuss models that explain the sudden change in eruptive activity since 2015	**Chapters Two, Four**
3	To investigate experiences of residents of communities near Fuego of (1) previous eruptive activity and volcanic hazards, and (2) their responses to the same	**Chapter Three**
4	To compare results from remote sensing data with peoples' experiences to understand how different perspectives influence volcanic risk at Fuego	**Chapter Three**
5	To evaluate how experience of and response to eruptive activity influence the success of current volcanic risk mitigation policy	**Chapters Three, Four**
6	To determine, through analysis of geophysical data, timescales associated with paroxysmal eruption in the new (since 2015) eruptive regime	**Chapter Four**
7	To explore timescales associated with response to recent eruptions	**Chapter Four**
8	To explore, by comparing the timescales above, the likelihood of current volcanic risk mitigation policy at Fuego providing sufficient warning to protect lives of local residents	**Chapter Four**
9	To consider (1) implications for the continued risk to lives and livelihoods of local residents from eruptive hazards associated with explosive paroxysms of Volcán de Fuego, and (2) opportunities to mitigate this risk	**Chapters Two, Three, Four, Five**

Table 5.1: Summary of thesis objectives from 1.2.3 with evidence of answers and their location in this thesis. Inspired by Hicks (2012).

5.2.1 Objective One: Characterizing recent eruptive activity of Fuego through satellite remote sensing data

The research in this thesis begins with a synthesis of literature on Fuego's eruptive activity through prehistoric, historic, and recent time periods. Research by Lyons et al. [2010] on patterns in eruptive activity at Fuego in 2005 – 2007 provided a clear foundation on which to build. The greater availability of MODIS data since 2010 and the development of additional processing methods have allowed for more refined studies of long-term changes in volcanic activity. A 12-year study of MIROVA data (derived from MODIS) at Stromboli [Coppola et al., 2012] that used statistical methods to categorize transitions between eruptive styles informed my research on Fuego. I triangulated statistically-derived patterns in MIROVA data with geophysical data

(RSAM) and bulletin reports, both from INSIVUMEH. The use of bulletin reports to corroborate geophysical observations is a fairly unusual method in physical volcanology literature.

My study provided definitive evidence for a new eruptive regime beginning at Volcán de Fuego in January 2015 (see Chapter 2.5). The new regime showed a remarkably high frequency of paroxysmal eruptions (12 – 16 per year) compared to previous years (2 – 4). Furthermore, MIROVA and bulletin reports revealed that paroxysms in the new regime were characterized by a novel three-stage sequence of events: (i) effusion of lava flows and increase in summit explosive activity, followed by (ii) an intense eruptive phase lasting 24 – 48 hours, producing a sustained eruptive column, continuous explosions, and occasional pyroclastic flows, followed by (iii) decrease in explosive activity. The very high correlation between lava flow effusion and subsequent paroxysmal eruption in these years prompt questions on what subsurface processes could drive such a marked increase in energy output (see next goal for detail). At the time this research was completed, Fuego was extremely poorly instrumented, with only one functioning seismometer (FG3). In the absence of a more comprehensive monitoring network that would yield a broader dataset, I advocated the pairing of remote sensing data with monitoring reports for understanding long-term changes in behaviour of poorly-instrumented volcanoes like Fuego.

5.2.2 Objective Two: Discussing models explaining the sudden change in eruptive activity since 2015

Because the previous chapter was the first comprehensive study of the accelerating cycle of paroxysms seen at Fuego since 2015, there was no comparative research that included models I could use to explain the acceleration. However, both earlier studies of long-term behavioural patterns at Fuego [Lyons et al., 2010] and studies using the same methods on analogous volcanoes [Coppola et al., 2012] discussed models that informed my research. I was also guided by my review of literature on Fuego's eruptive activity (see Chapter 2.3). While early scholars of Fuego advocated a simple system fed by discrete magma chambers [Rose et al., 1978], more recent literature advanced an idea of magma mixing across the full length of Fuego's conduit [Berlo et al., 2012]. The rise-speed dependent model proposed by Lyons et al. [2010] is consistent with both the greater effusion rates and more frequent paroxysms seen since 2015.

I proposed an alternative mechanism for triggering paroxysm at Fuego in 2015 - 2018. This was based on several instances observing summit conditions immediately before paroxysm. Paroxysmal eruption could be triggered by shedding of material from an ephemeral summit cone that causes a drop in confining pressure and spurs downwards-propagating fragmentation. On several field trips to Guatemala, I and others observed a cone of ballistic material in Fuego's summit crater. We surmised that the cone was created by accumulation of ballistic material from sustained lava fountaining. Once the summit crater filled, lava effusion down Fuego's flanks began. A sufficiently high lava effusion rate could destroy the summit cone and remove enough volume to depressurize the magmatic system, thus triggering a paroxysm. While this model would create the precursory lava flows and avalanches characteristic of Fuego's activity in 2015 – 2018, it cannot be a common triggering mechanism for all paroxysms in this period. There were several occasions when we observed a visible depression in Fuego's crater immediately before paroxysm. Even supposing an enormous effusion rate, on these occasions it would not have been possible for lava to fill and overspill the crater in the time window before paroxysm. As of July 2020, Fuego has not had a paroxysmal eruption since November 2018. It is therefore difficult to conclude whether paroxysms since 3rd June 2018 (when Chapter Two ended) follow the same pattern as their predecessors.

Observations in Chapter 4 also allowed me to debate the theory of Nadeau et al. [2011]. In recent paroxysms of Fuego captured by NicAIR there was no evidence to support short-term decrease in SO_2 degassing before explosion apparently due to rheological stiffening in Fuego's upper conduit. Nadeau et al. [2011] studied Fuego during a different period of eruptive activity, and my research does not doubt their explanation for Fuego's activity in 2009. However, it is doubtful that this explanation is valid for Fuego's activity in 2015 - 2018. The higher explosivity rate would mean that rheological stiffening would occur (and be overcome) across several minutes, which is unlikely.

5.2.3 Objective Three: Investigating experiences of residents of communities near Fuego to determine factors influencing evacuation

I was particularly enthusiastic about this research objective because I could fill a large gap in knowledge. My interviews end a hiatus of 13 years of qualitative volcanic risk research at Fuego since the study by Graves [2007]. This research goal was grounded in a thorough review of research paradigms in volcanic risk and of factors identified as influential in the decision to evacuate during volcanic crisis. This research objective was underpinned by my friendships with colleagues in INSIVUMEH and CONRED, and first conceived in 2017 when accompanying colleagues from CONRED's sub-department UPV to visit communities around Fuego. In contrast to the quantitative methods employed for previous research goals, I took an inductive approach to investigating local experiences. I employed qualitative methods, including semi-structured interviews, supplemented by ethnographic methods like 'conversations with a purpose' and participant observation. The methods and concepts I involved in meeting this research objective were greatly informed by previous studies at Katla volcano [Jóhannesdóttir and Gísladóttir, 2010], Mt. Merapi [Dove, 2008], and Volcán Tungurahua [Stone et al., 2014] (see Chapter 3.5).

This research yielded many surprising insights. The impact of the 1974 eruption has been acknowledged in previous literature (e.g., Rose et al. [2008]), but my work revealed that the 1966 eruption had been similarly devastating to communities on Fuego's western flanks. As a result of this, older people in the west regarded the 3rd June 2018 eruption as more minor than locals in eastern communities and were less likely to evacuate. Although many other studies have found that risk is heterogeneous around a single volcano (e.g., Donovan et al. [2012a]), the element of experience of previous activity and impacts at Fuego had not been explored prior to my work. Another important discovery of my research was that local people have a qualitative way of measuring volcanic risk at Fuego in the distinction of *arena/ceniza*. This is an intriguing result that promotes further investigation in multiple avenues. For example, investigation into the nuances of the *arena/ceniza* distinction at Fuego; into other hazards at Fuego (are there qualitative thresholds for when a lahar becomes dangerous?), and beyond Fuego, into whether local people use qualitative thresholds to determine tolerable thresholds of volcanic risk at other volcanoes.

An important component of this research objective was evaluating how local residents' decision-making regarding evacuation intersected with the current self-evacuation policy promoted by CONRED. I found that factors influencing local peoples' decision to evacuate at Fuego are consistent with those found in other literature, including fear of looting and worries about livestock welfare. In Chapter 3.7.2.3), I argued that the self-evacuation policy sits at odds with local priorities. Despite the excellent work that CONRED (via UPV) does in engaging with communities to provide volcanic hazard information and set up volunteer COLRED organizations, the premise of self-evacuation is fundamentally at odds with the existing socio-economic conditions that make people at Fuego vulnerable to risk and consequently less likely to evacuate until it is too late.

5.2.4 Objective Four: Comparing remote sensing and resident observations to understand different perspectives of volcanic risk at Fuego

I have been greatly influenced by a pioneering study on alternative perspectives of volcanic risk conducted at Mt. Merapi by Dove [2008]. In this work the author proposed "to compare and contrast views of volcanic hazard on Merapi volcano in central Java, Indonesia" [Dove, 2008]. A significant conclusion was the main difference between state and community gaze towards hazard vs non-hazard: state attention on Merapi spiked with an eruption, while community interest was almost the opposite, with the inter-eruptive periods capturing their attention. This seminal paper has received >100 citations for its careful exploration of the multiple conceptualizations of risk around a volcano. Furthermore, the author's assertion that state views of volcanic hazard are themselves socially constructed are important for considering the problems of volcanic risk mitigation from multiple directions.

Based on my friendships with both locals and INSIVUMEH/CONRED staff and my results from the previous research objective, comparing local and authority views of eruptive activity at Fuego seemed a fruitful avenue. A striking finding I made during my 2019 field season was that INSIVUMEH and CONRED staff had experiences of Fuego's activity that were very similar to results of satellite remote sensing data. Both observed a sharp increase in Fuego's paroxysmal frequency since 2015. This agreement is not solely attributable to INSIVUMEH/CONRED staff access to satellite data, as such data were not a principal component of INSIVUMEH's monitoring resources in 2019. It is more probable that this agreement between human and satellite observations was because of INSIVUMEH bulletins. I discussed the implications of the difference between local and authority views of risk (and local and remote sensing) in Chapter 3.7.1.1. Reconciliation of the different points of view is crucial for future risk mitigation at Fuego, but I argue it is the responsibility of INSIVUMEH and CONRED to work towards understanding and incorporating local perspectives among their monitoring and communication efforts, given their much greater resources and mobility than most locals around Fuego.

5.2.5 Objective Five: Evaluating how experience of and response to eruptive activity influence the success of current volcanic risk mitigation policy

Among all my thesis objectives, this objective has perhaps the greatest practical application, as evaluating the factors that influence whether current evacuation policy will be followed in the event of an eruption of Fuego can indicate current challenges to the success of the policy, and suggest appropriate methods to strengthen such policy. It is thus similar to the recommendations I refer to in Section 5.2.9. I evaluated how experience and response influence attitudes to self-evacuation in Chapter 3.7.2. I also answered this objective through discussion of timescales involved in eruption and response in Chapters 4.7.1 and 4.7.2.

5.2.6 Objective Six: Determining timescales associated with paroxysmal eruption in the new eruptive regime

My research in this chapter was informed by previous study of Fuego's activity using both ground-based methods [Nadeau et al., 2011] and satellite-borne instrumentation [Aldeghi et al., 2019] (see Section 4.3). In particular, work by Aldeghi et al. [2019] was an excellent precedent for my deductive approach to understanding recent paroxysmal eruptions at Fuego by combining geophysical and satellite parameters. Nevertheless, an important parameter missing from Aldeghi et al. [2019]'s study was SO_2. I believe this parameter is particularly important to study at Fuego because (1) it has been used extensively to study timescales of transition between effusive and explosive eruptive styles at analogue volcanoes (see Chapter 4.3), and (2) there were ample data available for Fuego in 2015 - 2018 thanks to consistent image capture by the NicAIR camera (Chapter 4.5). My particular excitement in pursuing this research goal was the prospect of delivering perhaps one of the first long-term analyses of SO_2 degassing using ground-based thermal spectroscopy at an open-vent volcano.

My first aim within this objective was to determine any consistent patterns in geophysical data relating to paroxysmal eruption. Through my interpretation of multiple geophysical datasets, I found that RSAM is a particularly consistent companion to eruptive behavioural changes during recent paroxysmal eruptions of Fuego. SO_2 data did not show obvious patterns related to paroxysmal eruptive activity, although SO_2 fluxes generally increased prior to paroxysm and decreased in days after. These observations were consistent with my hypotheses in Chapter 4.4. An effusive eruption in November 2017 provided an interesting opportunity to study an "anomalous" event in 2015 - 2018. This event was anomalous because all precursors to paroxysm occurred (as detailed in Chapter 2), but a paroxysm did not follow. Through careful analysis of the data, I observed that the sharp increase in RSAM associated with paroxysm did not happen in November 2017. I called this a “stalled” paroxysm. I discovered that SO_2 followed an inverse pattern to RSAM and peaked a few days after peak lava effusion. From this I suggested that further study may yield evidence for threshold values within geophysical parameters. A paroxysm may occur once these thresholds are crossed and a "runaway" effect occurs, perhaps of downward-propagating fragmentation within Fuego’s conduit. The “stalled” paroxysm of November 2017 represents an occasion where the energy of the system was not sufficient to cross the threshold into a fully-fledged paroxysmal eruption.

On the theme of determining patterns, I also aimed to determine any consistent sequence in hazards relating to paroxysmal eruption. The sequence of these hazards could determine over what timescales an eruption could evolve from low-risk (producing lava flows) to high-risk (producing pyroclastic flows). I found a strong correlation between lava flow effusion and pyroclastic flow descent in the same barranca. Incomplete satellite coverage and INSIVUMEH reporting can explain the few occasions when pyroclastic flow occurred in barrancas towards which lava was not directed. I briefly considered models to explain the correlation between lava flow and pyroclastic flow. These included pyroclastic flow generation from lava flow front collapse and summit crater morphology controlling direction of both flows. More detailed observations are necessary to validate this latter model. Although tentative, if these models are validated they could have important practical implications. Currently, INSIVUMEH’s Special Bulletins include general warnings to avoid barrancas because of the possibility of pyroclastic flow descent in any barranca. If summit morphology were confirmed as a control on direction of lava and pyroclastic flow movement, INSIVUMEH would be able to tailor their reports to acknowledge heterogeneous levels of volcanic hazard around Fuego (see Chapter 4.8).

Previous work on timescales of eruption at Volcán Tungurahua [Armijos et al., 2017] and at Fuego itself [Aldeghi et al., 2019] informed the method and format of timescales of eruption I presented in Chapter 4.6.1. Using three paroxysmal eruptions and one effusive eruption in the 2015 - 2018 cycle, I was able to determine a range of timescales for different periods of activity within the evolution of an individual eruption, including acceleration to paroxysm, climactic period, and reduction in activity. I acknowledged various sources of uncertainty in these timescales, including instrumental error, cloud cover, timing of eruption during day or night, and absence of personnel. Despite myriad sources of uncertainty, the use of multiparametric timeseries to explore timescales of eruption provided informative results.

While my efforts to determine patterns in geophysical data yielded some interesting results, I found it my most frustrating goal. Cloud cover at Fuego's summit and operational issues reduced both the quantity and quality of data captured by NicAIR. My goal of studying paroxysmal eruptions in detail was hindered because despite >100 days of data capture, only a very few paroxysms were captured. NicAIR often seemed perverse, shutting off just as Fuego's activity was becoming interesting. Even when working with data of good quality, I found NicAIR data processing computationally intensive. Nevertheless, I believe that SO_2 monitoring should be included within INSIVUMEH's monitoring capacity. Consistent SO_2 flux data would allow for more detailed exploration of Fuego's subsurface processes that could inform future forecasting efforts.

5.2.7 Objective Seven: Exploring timescales associated with response to recent eruptions

This objective is closely tied to the previous one. I used a study of response timescales at Volcán el Chichón [Marrero et al., 2013] as a framework, and interviews with local residents combined with timelines provided the data for exploring response timescales at Fuego. These provided a series of timescales for steps in the evacuation process, i.e., response to eruption (see Chapter 4.6.4). By comparing these timescales with those presented in Chapter 5.2.6, I determined that timescales of eruption and response are comparable at Fuego. While it is in theory sufficient that prediction of eruption occurs on timescales comparable to responses that people can take [Fournier d'Albe, 1979], in reality there are many factors that delay or complicate steps in the evacuation process, such that the required evacuation time presented by [Marrero et al., 2013] is not possible during eruptive crisis at Fuego. These factors include difficulty in making the decision to evacuate (explored in both Chapter 3.7.2 and Chapter 4.7.2), the long timescale involved in evacuating on foot (Chapter 4.7.2), or the possibility that residents following the official evacuation route for their community actually pass through a zone of higher risk during evacuation (see Chapter 4.7.2). The implications of these timescales for volcanic risk to local residents are discussed in the following section.

5.2.8 Objective Eight: Exploring the ability of current volcanic risk mitigation policy to provide sufficient warning to protect lives of local residents

This objective is the culmination of results from previous objectives, and strikes to the heart of the matter at Fuego: the ongoing risk to lives of local residents. In Chapter 1, I stated that a primary purpose of writing this thesis was to contribute to the future security of people living in rural communities around Fuego (see Chapter 1.2.2). Both the factors affecting evacuation explored in

Chapter 3.7.2 and the timescales presented in Chapter 4.6.5 present a scenario where significant challenges exist to the successful realization of the self-evacuation policy in future large eruptions of Fuego. Action is needed. Recommendations to strengthen volcanic risk mitigation at Fuego are introduced below and explored in Section 5.3.

5.2.9 Objective Nine: Considering the continued risk to residents from hazards associated with activity of Fuego, and opportunities to mitigate this risk

Evaluating current volcanic risk mitigation policies at Volcán de Fuego is worthy of a whole thesis itself. However, through reference to literature studied in Chapter 3.4, and results from locals, I was able to suggest the main challenges to the successful realization of current volcanic risk mitigation policy at Fuego. In particular, Chapter 3.7.2.3 explores the difficulties in successful evacuation of local residents from an eruptive crisis of Fuego. Below, Table 5.2 summarizes these difficulties and presents some potential solutions.

My recommendations are specific to Volcán de Fuego. For consideration of how research presented in this thesis could be transferred to volcanoes beyond Fuego, see Section 5.5.

5.2.10 Thesis limitations

Each of the chapters in this project had shortfalls which I hope will inspire future research at Fuego. The period under study in Chapter 2 ends with the 3rd June 2018 paroxysm, which was different from previous eruptions. In this chapter's discussion, I suggested this paroxysm could conclude the new eruptive regime that began in January 2015; however, two eruptions followed in October and November 2018. Including these paroxysms in the period under study could contribute to the understanding of the subsurface processes driving the cycle, and determine whether the 3rd June eruption caused the end of the cycle.

In Chapter 3, I wished to capture the stories of people living around Volcán de Fuego as told in their own words. Although it is a long chapter, I was only able to include a few of the many experiences and stories that I listened to. The qualitative methods I employed are not supposed to give a representative view of volcanic risk, but to capture richness and depth in lived experience. One flaw in my qualitative research was a shortfall of experiences from older people; in particular from those living on Fuego's eastern flanks in communities like Ceilán. This shortfall was understandable given the short duration of my field season (nine weeks in 2019, with an additional two weeks across several earlier visits). I have great hopes that future researchers will prioritize gathering and preserving experiences of locals around Fuego. Given the current age of locals who remember the eruption of 1974 and its aftermath, there is little time to record these voices before they are lost. My short field season also prevented further research into cultural volcanology (as pioneered by Donovan [2010]). I would have liked to explore in detail the culture of Ceilán, whose distinctive practices surrounding Fuego – candlelit vigils in 1974, pilgrimages to the cemetery, the spiritual importance of El Cucuruchu – left an indelible impression on me. Both Ceilán and its neighbour La Rochela, several hundred metres down the road, make a wonderful microcosm on the diversity of experience and heterogeneity of risk around an active volcano. I hope that future research will also consider juxtaposing Ceilán and La Rochela: the idiosyncrasies of two communities so close, but so different in their approach to risk and their interaction with authorities, would make a fascinating subject for study.

Chapter 4 used data from NicAIR to contribute to gas and geophysical timeseries at Fuego between 2015 and 2018. Incomplete data capture is a limitation to the quality of the data. The major improvement in INSIVUMEH's monitoring capacity since 3rd June 2018 means that studies of eruptive evolution at Fuego involving multiple geophysical datasets will be much more detailed. Future collaborations with Guatemalan volcanologists to co-produce studies using these data would produce detailed new insights into Fuego's subsurface. Although INSIVUMEH now boasts a geophysical network including multiple seismometers and infrasound, they do not have capacity for near-real-time SO_2 detection. In my opinion, this should be a priority for future research at Fuego. In particular, the development of cheap and portable spectroscopic instruments including the portable UV smartphone camera (PiCam), and an IR version currently in development (PiRcam), should be prioritized. Chronicling Fuego's emissions with these cameras has promise both for advances in academic understanding and for practical hazard mitigation. Another limitation in Chapter 4 was the large uncertainties involved in estimating timescales of response to eruption. While individuals gave clear estimates of certain processes involved in evacuation, these did not necessarily match the processes involved in models of timescales I used to guide my work [Marrero et al., 2013]. Part of this uncertainty is inherent due to the difference between modelling hypothetical evacuation scenarios and mapping previous evacuation experiences. Other uncertainty is because interviews were initially designed to gather narratives of qualitative experience, rather than of quantitative timescales. The relative richness of information on timescales gathered from interview data is a unexpected benefit of the study, primarily designed for Chapter 3, and a tribute to the value of such research as discussed in Chapter 1.2.

5.2.11 Summary of thesis contributions

This thesis has charted the eruptive behaviour of Volcán de Fuego in 2015 - 2018. It has provided new knowledge on the experiences of people living in Fuego's shadow, and shared testimonies from scientists and DRR staff working with local residents. While the thesis originally concentrated on a few years of eruptive activity, its qualitative and quantitative findings extend beyond this narrow focus. Fuego's new eruptive cycle is better understood in the context of preceding activity. I initially designed my qualitative study to gather testimonies of eruptions since 2015, but people wished to share stories of both recent eruptions and those drawn from decades of living beside the volcano.

5.3 Further work at Volcán de Fuego

One of my personal aims in this thesis was to use my findings to improve communication between different stakeholder groups at Volcán de Fuego. The recommendations below are not intended as a critical evaluation of CONRED's and INSIVUMEH's roles – which is beyond my expertise as a researcher. Rather, they summarize the challenges of obtaining a holistic view of volcanic risk at Fuego, and several recommendations are to other researchers who are interested in carrying this work forward. For transferability beyond Volcán de Fuego, see Section 5.5.

	Issue	**Explanation**	**Other literature**	**My suggestions**
1	Difference in conceptualization of risk	Locals conceptualize volcanic risk as occasional/secondary (only largest eruptions require response); INSIVUMEH/CONRED consider volcanic risk volatile/primary.	Dove (2008); Dibben (2008)	More research into conceptualization of volcanic risk (consider longitudinal and cultural elements)
2	Difference in understanding what constitutes an eruption	Locals identify as eruptions only those requiring evacuation. INSIVUMEH/CONRED identify eruptions similar to remote sensing data.	None?	More research on conceptualization of eruptive activity
3	Lack of shared thresholds of tolerable risk	Locals will evacuate “when risk is high enough” but have no strict threshold (barring *arena*/*ceniza* – see 5). INSIVUMEH/CONRED have shared threshold of pyroclastic flow descent with La Reunión only.	van Manen et al. (2014); Armijos et al. (2017)	Participatory workshops for shared decision of risk thresholds
4	Lack of shared vocabulary	Locals have no word for pyroclastic flows, instead refer to “humazon”/“humo”. Authorities use technical language inc. “pyroclastic flows”.	Armijos et al. (2017)	Continued visits by UPV with videos and demonstrations
5	Previous direct experiences of eruption	Locals influenced by activity/impacts of 1966/1974 eruptions in future decisions on evacuation. Authorities diminish importance of these influences.	Wachinger et al. (2013); Lechner & Rouleau (2019)	Spaces for people to share experiences (videos, music, *intercambios*, storybooks
6	Outsourcing of trust to INSIVUMEH (W flanks)	Locals trust INSIVUMEH and OVFGO1, therefore outsource risk to authorities	Wachinger et al. (2013)	More research on responsibility for evacuation
7	No INSIVUMEH presence on E flanks	Locals on E flanks do not have regular communication with INSIVUMEH	None?	Installation of observatory and observers on E flanks
8	"Push" and "pull" factors	- Local people inclined to return from evacuation by "push" (e.g., shelter conditions) or "pull" (e.g., looting, crop damage, livestock health) factors	Barclay et al. (2019)	Livestock welfare aid; crop diversification; adaptive evacuation plans
9	Lack of resources to evacuate	Evacuation difficult for resource reasons, e.g., vehicles or documents not immediately available.	Mei et al. (2013)	Various. Buses from *ingenios*?
10	Inconsistent trust	Local trust in authority heterogeneous	Donovan et al. (2012)	Strengthening COLRED/UPV communication

Table 5.2: Ten impediments to successful volcanic risk mitigation at Fuego w.r.t. evacuation from eruption producing pyroclastic flows. From my observations in Guatemala since 2016.

5.4 Reflections on the value of an interdisciplinary study

This project is one of a very few interdisciplinary volcanology theses. It integrates methodologies from physical and social sciences in order to paint a holistic portrait of volcanic risk at Volcán de Fuego. This interdisciplinary thesis has been guided by a few predecessors, who vary in their level of integration of different disciplines from those designed as interdisciplinary from the outset [Hicks, 2012], to those that pair methodologies from different disciplines without an extensive study of the disciplines involved and philosophical approaches within Escobar Wolf [2013]. This thesis follows a middle path between those two end-members. In Chapter 1 I present alternative philosophies of knowledge, along with methodologies involved in those approaches. As a researcher I carry influences that include my nationality and gender, and incorporate both deductive and inductive approaches to gathering evidence. This whole-hearted positionality was inspired by the reflections of Anna Hicks in her thesis [Hicks, 2012]. However, the order of the thesis chapters show a juxtaposition of physical science and social science that is more similar to the thesis structure of Escobar-Wolf [Escobar Wolf, 2013].

There are drawbacks and benefits that attend this middle path. One drawback is that focussing on a single topic could have generated a more complete analysis – for example, a more comprehensive study of SO_2 degassing patterns in Fuego's recent eruptive history. However, one could conversely argue that a better understanding of degassing patterns is highly relevant to volcanic risk as it contributes to the understanding of physical behaviours and related hazards that may have impacts on nearby populations. In this way, analyses of physical processes like SO_2 degassing are contextualized by the impacts that they may have for people nearby. Understanding that knowledge of physical processes must be embedded in the wider portrait of volcanic risk means acknowledging a complex situation. This is the main benefit of conducting an interdisciplinary study – of rendering a more faithful portrait of a volcano by recognizing multiple perspectives of volcanic activity and risk that are all different, but also all valid. It has been acknowledged that both social and physical scientists approaching volcanic risk miss part of the whole story [Donovan, 2019]. While my thesis is in no sense a resolution of the two partial views, by having a foot in each discipline it does acknowledge the multifaceted and intertwined challenges of studying risk at an active volcano.

Choosing an interdisciplinary study is valuable not only for recognizing complexity in the research, but also in recognizing the complexity in the researcher's role. During this thesis I have followed an initial interest in tracing Fuego's eruptive activity and physical hazards, through consideration of how this activity begins and evolves, to capturing the various ways in which this activity is experienced by different people. The developments in my research has attended my evolution from a geologist grounded in the assumptions and philosophy of natural science, towards a researcher who can identify with the philosophies and approaches to knowledge acquisition of both the natural and the social scientist. I have found this 'boundary crossing' both as exhilarating and as uncomfortable as Katherine Donovan, who used the term in her article on “bridging the geo-divide” [Donovan et al., 2011]. I was aware from the beginning that this transition was a fundamental part of my project, as it formed part of the project description:

> The project will develop a new breed of researcher, conversant in physical volcanology, geophysics, DRR and social dynamics which will present abroad range of challenges to an exceptional student.

The full project description appears in Appendix A (Chapter 6). I was motivated to apply because of the interdisciplinary nature of the project. I did not know how difficult it would be to work across several disciplines. Like Katherine Donovan, I was warned by several people that it would be dangerous to venture across disciplines at this early stage of my career, and should initially train in one discipline before broadening my focus [Donovan et al., 2011]. Ultimately, I found that the balm for the "growing pains" of working between disciplines was focussing on the value that I hoped the research would achieve. When acknowledging my unfamiliarity with social science concepts, or facing up to my limitations in conducting my physical science research, I could always refresh my enthusiasm by considering how my work could be of service in improving the situation around Fuego. In returning to how future risk from eruptions from Fuego could be mitigated, it did not seem to matter so much from which angle I approached the question, as long as I believed and could see that my work would contribute to the debate.

5.5 Reflections on the transferability of the case study

This thesis has used Volcán de Fuego as a case study for exploring the intersection between eruptive activity and human experience at an active volcano (see Figure 5.2). The case study highlights several of Fuego’s idiosyncrasies, including the unusually large variety of volcanic hazards it displays, and the vastly different ways in which even geographically close communities have experienced previous volcanic eruptions. Despite such idiosyncrasies, I believe that several concepts explored in this thesis can be applied to volcanoes beyond Fuego. For example, my findings on the diversity of direct experiences of previous eruptions (and the implications for future success of evacuation) follow from explorations of the culture of risk at Mt. Merapi by Kate Donovan [Donovan, 2010, Donovan et al., 2012b]. Volcán de Fuego and Mt. Merapi are only two active volcanoes with rich local culture among nearby populations, and many volcanoes in the Global South (e.g., across Africa, South America, and SE Asia) fit this profile but have not benefited from recent research focus. I would welcome future in-depth case studies of volcanic risk at individual volcanoes in these areas, because such studies would indicate that volcanology acknowledges the locally specific nature of volcanic risk. I also believe that this case study is transferable in the methods used. The methods I have used are simple and include data that is widely available data. MIROVA, for instance, traces activity of 213 volcanoes worldwide, and its owners actively welcome collaboration and new investigation. Other transferable resources in this thesis include the questionnaires that generated findings in Chapter 3, which I are simple and adaptable. I encourage anyone who is interested to use them (find them in Appendix D (Chapter 9)). Finally, I believe that this research provides a template for future interdisciplinary projects in volcanology. This thesis demonstrates both the difficulties of conducting interdisciplinary research and the immense rewards if one perseveres.

FIGURE 5.2. The intersection between human experience and volcanic activity. Taken in February 2017 during my first visit to Guatemala. Shows people resting in the shade beside the football pitch above INSIVUMEH's OVFGO1 observatory in the village of Panimaché Uno, Chimaltenango.

5.6 *Un paso adelante:* looking beyond Fuego for global examples of multiple stakeholder involvement in volcanic risk mitigation

Dialogue is crucial for growth. Just as Section 5.5 considered how conclusions from this case study could be applied to volcanoes other than Volcán de Fuego, this section discusses how stakeholder interactions at other volcanoes can inform current policy and risk mitigation practise at Fuego. Some of these interactions are: a greater involvement of local people in risk mitigation, technological fixes, and integration of volcanic hazard into a holistic approach to natural hazard mitigation.

Local people can be involved in volcanic risk mitigation as either individuals (e.g., as either actors or citizen scientists) or as members of a community. Locals as individual actors can feel empowered. An innovative film series created by the interdisciplinary Strengthening Resilience in Volcanic Areas (STREVA) project casts people at Nevado del Ruíz and La Soufrière volcanoes as protagonists and their experiences of volcanic activity as the narrative (`https://streva.ac.uk/`). These films are highly unusual in their approach to hazard communication. By using familiar voices to communicate risk, the films have given local people capacity to express themselves and to build resilience [Hicks et al., 2017]. A similar video appeared recently at Volcán de Fuego, sharing experiences of the people at La Trinidad (`https://bit.ly/3ehxe8U`). Although this video speaks more of loss and fear than of resilience, it is important to hear these voices too.

The benefits of engaging local people in citizen science projects for volcano monitoring is explored in Stone et al. [2017]. Such projects may be realized in several ways, including through Tungurahua's *vigía* network [Stone et al., 2014] or through participatory workshops [van Manen et al., 2015, Cronin et al., 2004]. Citizen science projects continue to be a popular tool in interdisciplinary volcanological research and are included in several current GCRF projects (e.g., GCRF Challenge Clusters – Risk at the Margins: a blueprint for de-fragmenting disaster risk reduction with populations at risk). As stated in Fearnley et al. [2018]: "Participatory risk management involving community leaders and their populations is most appropriate to bridge tradition, local realities and the implementation of risk management policies and strategies". Figure 5.3 shows the importance of integrating scientific and indigenous knowledge to decrease vulnerability from natural hazards.

My strong belief in the necessity of integrating indigenous and scientific knowledge comes from personal experience. I was transformed by an accidental visit to Colombia in October 2019 that gave me unexpected insight into the country's volcanic risk mitigation practices[1]. My meetings with staff from UNGRD (*Unidad Nacional para la Gestión de Riesgos*), the Colombian analogue to CONRED, made a particular impression on me. In the 35 years since the tragedy of Nevado del Ruíz in November 1985, UNGRD has worked to build relationships with various indigenous communities who live around the country's many volcanoes. These include cultural dialogues (music, community museums), regular visits, and digital products (`http://www.volcanriesgoyterritorio.gov.co/`). UNGRD has a prescient approach to volcanic vocabulary. For example, the institution discovered that indigenous communities refer to pyroclastic flows as *"avalanchas calientes"* ("hot avalanches"). Whatever this term loses in precision, it gains in utility, because the two groups can talk about a hazard using a common language. While the importance of shared vocabulary to developing shared thresholds of tolerable risk has been the subject of academic study [Armijos et al., 2017], seeing these findings translated to policy has given me great hope for future collaborative efforts in volcanic risk mitigation.

There are technological as well as social solutions to volcanic risk mitigation. Local people have

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[1] I planned to attend the inaugural ALVO conference in Antofagasta, Chile, until it was cancelled by nationwide demonstrations. I learned of the conference's cancellation while in the immigration queue in Bogotá's El Dorado airport.

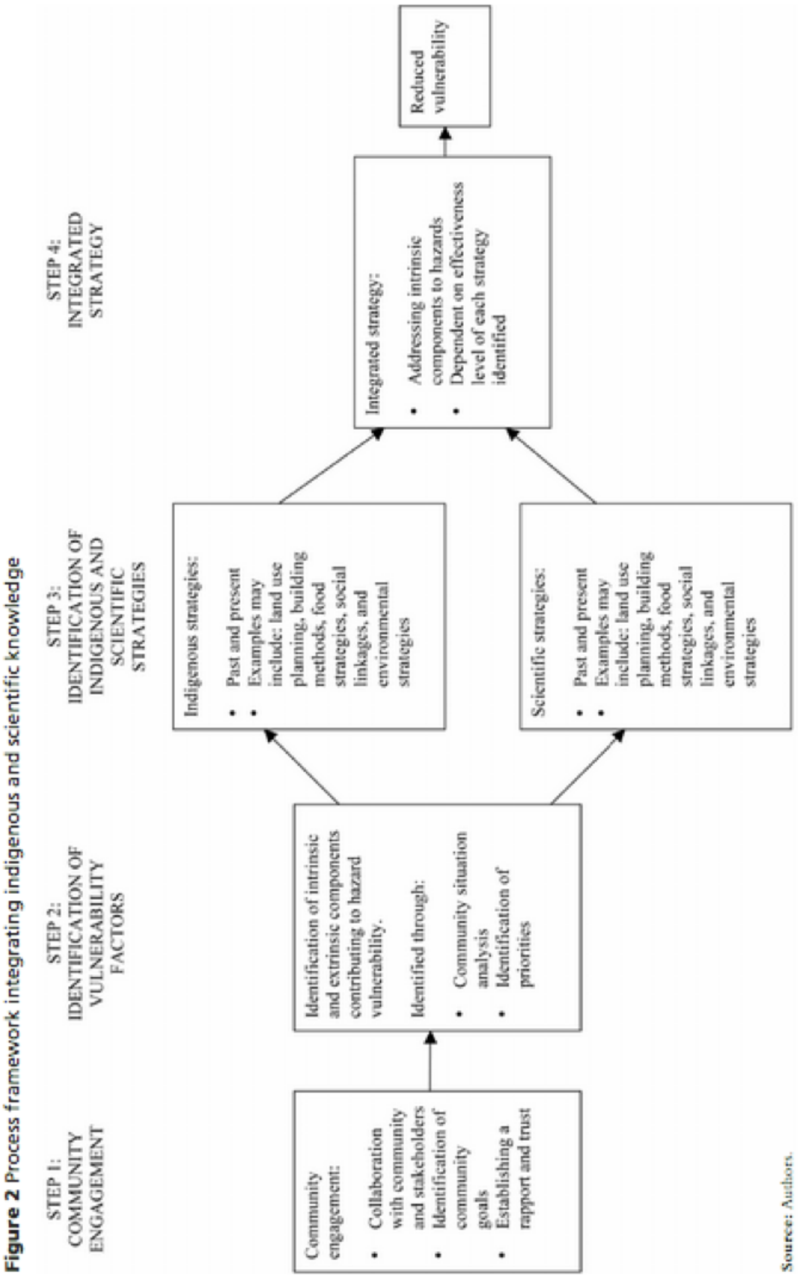

FIGURE 5.3. Process framework integrating indigenous and scientific knowledges to tackle vulnerability. From Mercer et al. [2010].

a great store of untapped knowledge that should be included in future mitigation efforts. But the involvement of citizen scientists must be in parallel to better support for volcanologists. Abroad of Fuego, multiple initiatives have made clever use of technology to help scientists communicate their research outside of their sphere. In several of these, communication is bilateral, so the scientists can receive feedback. A good example of this is GNS Science, a government-owned private organization in New Zealand that provides an open and responsive service that makes it easy to contact scientists directly. (Of course, New Zealand has several social and economic advantages that make its volcanic risk mitigation policies distinctive and locally applicable, including a stable political system and small population.)

"Better communication" is often cited as key in improving volcanic risk mitigation. However, the specific methods of *how* to communicate better are rarely discussed. This is because "communication" is not a single challenge but multiple issues, involving questions of culture, language, uncertainty, and responsibility (among many other factors) [Barclay et al., 2008]. A fundamental point is that best practice for volcanic risk communication will not be consistent, even within a single nation [Andreastuti et al., 2019]. The challenge of how to communicate volcanic risk is so current that a 2019 paper was dedicated to this [Pallister et al., 2019]. In order to improve communication pathways between scientists and the public, it is widely agreed that scientists should be open and honest [Pallister et al., 2019]. Trust is crucial for good communication between scientists, authorities, and the public [Christie et al., 2015]. This trust is established with time. Therefore, permanence of scientists at institutions is an extremely important part of bettering communication. This permanence allows for retention of specific knowledge and experience, very important because the longer a scientist stays at an institution, the more lived experience they accumulate – and lived experience is a currency common to local people. It is good to advise volcanologists to be clear and honest in their communications. However, it should be acknowledged that volcanologists often hold a difficult position where they are both a trusted voice and a perceived source of knowledge that may hold more uncertainty than desired [Donovan et al., 2014]. IAVCEI's guidelines on Crisis Protocols (IAVCEI, 2016) include this recommendation: "IAVCEI recommends that scientists ... safeguard not only their own legal status, but also the status and credibility of their advice which should be independent, neutral, objective, unbiased, and value-free". How should a scientist (a human with their own set of values) try to follow such advice? It is impossible – and, I would argue, not recommended. One lesson for physical scientists in the interface between volcanic activity and human experience is that 'bias' is not inherently negative. In fact, acknowledging one's positionality can strengthen one's position. I learned this myself during the course of this thesis. Social scientists have long been aware of this point, and may hope to convince physical scientists of it in their future interdisciplinary projects.

The solutions that this section proposes (acknowledging multiple perspectives, encouraging local participation, and supporting advances in scientific monitoring and communication to people outside their sphere of knowledge) are not limited to volcanic risk. They may be appropriate strategies for mitigating risk associated with multiple other natural hazards such as flooding, hurricanes, and landslides – sometimes all in a single environment [Mercer and Kelman, 2010]. I believe that volcanic risk, and volcanic risk perception, are too frequently studied in isolation (see 3.4 for my criticism of "volcanic risk perception" as a concept). By considering volcanic activity as one of many natural hazards to which people are vulnerable, volcanologists can make themselves open to advantages and strategies that exist outside their immediate field. For example, recent research on marginalized groups that are vulnerable to flood hazard in Nepal and Peru presents an exciting new approach for amplifying voices of those who are disproportionately vulnerable to impacts of natural hazards [Brown et al., 2019].

5.7 Final thoughts: modern challenges in volcanic risk mitigation

Humanity exists in a delicate balance with the natural environment. The accelerating interest in interdisciplinary natural hazards research shown in Figure 5.1 suggests that we are beginning to appreciate our mutual influence. There is evidence for both humanity's vulnerability and resilience to natural hazards: while natural hazards continue to cause death and damage in increasing scale [Formetta and Feyen, 2019], data show a decreasing trend in social and economic vulnerability to natural hazards over the last three decades [Formetta and Feyen, 2019]. However, this trend is not equal across the globe: in 2020 there is a large natural hazard vulnerability gap between poorer and richer countries [Formetta and Feyen, 2019]. Anthropogenic processes are recognized as both triggering and influencing various natural hazards [Gill and Malamud, 2017]. Although research into the extent of this influence is in its infancy, there is some evidence that future extreme natural events linked to anthropogenic climate change will be unevenly distributed across the globe, with lower-income countries experiencing effects at earlier thresholds than higher-income countries [Harrington et al., 2018]. Widespread acknowledgement that human activity profoundly influences the natural environment has prompted support for recognizing a new geological epoch, the "Anthropocene" [Lewis and Maslin, 2015]. This term has not been universally adopted. However, it is my opinion that we should entertain the concept of the Anthropocene, because it involves a fundamental shift in the relationship between humanity and the Earth [Lewis and Maslin, 2015]. With this concept we accept the mutual influence of humanity and the natural environment, and may accept that we are both subject to, and architect of, the future of this relationship. In the context of volcanology, acknowledging the Anthropocene (and consequently the close relationship between people and the environment) may facilitate approaches to volcanic risk mitigation that suit both the specific volcanic environment and those who earn their livelihoods in its surroundings:

> The problems of the Anthropocene — an interconnected, human-physical world — require post-normal, critical approaches that embrace reflexivity and acknowledge the embedded, situated nature of knowledge production and evolution. Creating such approaches requires the availability of open spaces for exchange of ideas, debate and discussion between different knowledge communities.

[Donovan, 2019]

Several of the hypotheses I proposed in preceding chapters have both been supported by evidence and encountered several arguments. For example, Chapter 4 presented some evidence for patterns in geophysical datasets for recent paroxysmal eruptions, but also a large variability in the magnitude and duration of these trends; meanwhile, Chapter 3 showed how collective memories of 20th-century eruptions could influence decisions of local residents decades later, but also how experiences of volcanic activity could differ greatly between individuals in the same small rural community. In my opinion, when read consecutively the chapters of this thesis grow more complex. I believe this complexity should not be feared. Instead, it is necessary to embrace this complexity in order to meet the challenge of volcanic risk in an increasingly interdependent world. Much of our success will depend on effective and considered collaboration with local partners:

> Greater focus is required on place-based solutions that emerge from the collaborative development of contextual warm data based on self-organizing around actions that are co-created, with local ownership of data, risks and solutions. Local capacity can be significantly increased by drawing from collective intelligence and mutual learning.

[UNDRR, 2019]

CHAPTER

6

APPENDIX A: INITIAL PROJECT DESCRIPTION

This first appendix shows the original project description of the PhD hosted within the NERC DTP GW4+ program. I applied for this project in February 2016 and began the program in Bristol on 18th September 2016.

Improving volcanic risk mitigation at Fuego Volcano, Guatemala

Supervisors

Main supervisor: Doctor Matthew Watson (University of Bristol)
Co-supervisor: Mr Gustavo Chigna (INSIVUMEH - Instituto National de Sismologia, Vulcanologia, Meteorolgia y Hidrologia, Guatemala - http://www.insivumeh.gob.gt/

INSIVUMEH is the national institute for natural hazards in Guatemala with responsibility for monitoring and mitigating risk posed by volcanic hazards. Gustavo Chigna is head of the volcanology section (made up on 1.5 FTE) with responsibility for 3 active volcanoes and >1,300,000 lives (the number of people who like within 10 km of a volcano in Guatemala, note this number does not include hazards with larger footprints e.g. distal ashfall).

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Project enquiries - Email: matt.watson@bristol.ac.uk **Contact number:** +44 (0) 0117 3315009

Host Institution: University of Bristol

Project description

Guatemala is ranked as one of the most high risk regions in the world with respect to volcanic hazards, with 22 Holocene volcanoes, of which 3 are currently active, high population exposure indices and only low levels of monitoring (Aspinall et al., 2011). Societal responses to elevated activity are made under duress with great uncertainty. It is testament to the skill and experience of, and trust in, local volcanolgists that community-lead evacuations, such as the one prompted by the pyroclastic flow in the image below, are typically calm and effective.

Fuego volcano is one of the most active volcanoes in the world with a population of > 200,000 living within a zone of high risk. We will deploy instrumentation owned by the Bristol Volcanology Group (two UV cameras, three differential optical absorption spectrometers (DOAS) and two forward looking infrared (FLIR) cameras) and a suite of portable Optical Particle Counters (OPCs), with the local observers from INSIVUMEH (Instituto National de Sismologia, Vulcanologia, Meteorolgia y Hidrologia), to make measurements of gas and ash emissions, thermal flux and exposure to particulates at populated sites around the volcano. The PhD student will co-ordinate their deployment and manage and process the data, along with seismic data, in collaboration with INSIVUMEH.

The data will be used to develop improved models of volcanic activity at Fuego, risk mitigation strategies for reduction of exposure to respiratory health risks, and improved evacuation strategies. Bayesian game theory and applied quantitative risk assessment (QRA) will be used to optimise future evacuations, based open several significant events in the last fifteen years. The PhD builds on previous work, including a QRA of the closest settlement, two projects on the analysis of FLIR data at Fuego; a study of social vulnerability at Merapi volcano; and a study linking lahar model outputs to effective, rapid decision making.

This project is novel and timely and develop an end-to-end process for risk management where the local population, through citizen science, have considerable ownership of data acquisition. It also represents a move towards recommendations made under the Sendai Framework around disaster risk reduction (DRR). The project will develop a new breed of researcher, conversant in physical volcanology, geophysics, DRR and social dynamics which will present a broad range of challenges to an exceptional student.

Aspinall, W., et al. Volcano hazard and exposure in GDRFF priority countries and risk mitigation measures-GFDRR Volcano Risk Study. *NGI Report*20100806.2011 (2011): 3.

CHAPTER 7

APPENDIX B: TABLE OF VEI ≥ 2 EVENTS 1524 - PRESENT

Table of notable eruptive events (VEI ≥ 2) at Volcán de Fuego in historic (16th – 20th century) and recent (1999 – present) periods. **Date** gives start of eruption and (whenever possible) end. **VEI (Est)** is determined from original sources, bulletin reports, and DRE volume. **Activity** provides a detailed account of eruptive activity from source material. Volume estimates within the Activity column cited with are derived from results obtained from mapping deposits of past eruptive events at Fuego (see Tables 2.1, 2.2, and 3.1 in Escobar-Wolf (2013) Escobar Wolf [2013]). Source provides information sources; sources are original whenever possible. All distances referenced are in kilometres from summit crater of Fuego. Italicised sources are secondary; for example, Escobar-Wolf (2013) represents a source cited in Escobar-Wolf's thesis. (probable) refers to eruptive phenomena that are not explicitly stated in historic records but are inferred by the authors of this paper from characteristics of the eruption described. In this table, (probable) most frequently refers to pyroclastic flows: the word "lava" is frequently encountered in historic records of Fuego's activity, referring to eruptive phenomena with characteristics that seem more likely to be pyroclastic flows e.g. several flows of "lava" are observed descending flanks of Fuego at great speeds, or carrying with them both fine ash and bombs.

Date	**VEI (Est)**	**Activity**	**Sources**

3 Jun 2018	3	Large eruption producing extensive pyroclastic flows (initial volume estimate of ≤ 0.05 km^3 in all barrancas) reaching >12 km from summit. Eruption begins with explosive activity at summit, followed by pyroclastic flows descending W barrancas of Fuego. Later pyroclastic flows descend barrancas on E flanks of Fuego, eventually causing destruction of La Reunion golf resort (5.9 km from summit) and community of San Miguel Los Lotes (8.9 km). Approximately 3,500 people evacuated. Official death toll of 113 with 332 missing.	GVP (2018), CONRED (2018), INSIVUMEH (2018)
5 May 2017	3	Large explosive eruption producing pyroclastic flows descending Barrancas Las Lajas, Trinidad, Ceniza and Santa Teresa. Residents of community of Sangre de Cristo evacuated.	GVP (2017)
12 – 13 Sep 2012	3	Large eruption producing lava flows and pyroclastic flows reaching 7km from summit in Barrancas Las Lajas and Ceniza. Extensive ash fall over communities to SW of Fuego. Approximately 10,000 people evacuated. Best estimate for mapped pyroclastic flow volume produced by eruption is 0.0269 km^3.	GVP (2012), Escobar-Wolf (2013)
15 Dec 2007		Large eruption. Best estimate for mapped lava volume produced by eruption is 0.0047 km^3.	INSIVUMEH (2012), Escobar-Wolf (2013)
7 – 9 Aug 2007		Eruption producing ash, lava, and pyroclastic flows in several barrancas. Evacuation of seven people. Best estimate for mapped pyroclastic flow volume produced by eruption is 0.0031 km^3.	INSIVUMEH (2012), Escobar-Wolf (2013)
5 – 8 May 2006		Eruption. Best estimate for mapped pyroclastic flow volume produced by eruption is 0.0018 km^3.	Escobar-Wolf (2013)
16 – 18 Jul 2005	2	Explosive eruption producing pyroclastic flows in Barrancas Santa Teresa, Taniluya, and Ceniza. Best estimate for mapped pyroclastic flow volume produced by eruption is 0.0037 km^3.	GVP (2005), INSIVUMEH (2012)
9 – 10 Jan 2004		Eruption. Best estimate for mapped lava volume produced by eruption is 0.0012 km^3.	Escobar-Wolf (2013)

29 – 30 Jun 2003	2	Eruption producing pyroclastic flows, lava, and ash fall. Large pyroclastic flows descended on Barranca Santa Teresa. Best estimate for mapped pyroclastic flow volume produced by eruption is 0.0122 km^3.	GVP (2003), INSIVUMEH (2012), Escobar-Wolf (2013)
6 – 9 Jan 2003	2	Eruption producing pyroclastic flows in Barranca Santa Teresa. Volume of deposits fill barranca and provoke declaration of a high-risk zone and evacuation of at least one house. Best estimate for mapped pyroclastic flow volume produced by eruption is 0.0053 km^3.	GVP (2003), INSIVUMEH (2012), Escobar-Wolf (2013)
21 May 1999	2	Eruption producing eruptive column and pyroclastic flows. Ash fall in Yepocapa, Alotenango, Santa Lucia Cotzumalguapa (depth 10-40 cm). Lahars in rainy season following eruption cause one death and damages to infrastructure. Best estimate of mapped pyroclastic flow volume produced by eruption is 0.0254 km^3.	GVP (1999), Escobar-Wolf (2013)

10 – 23 Oct 1974	4	Extremely large eruption involving a 'cluster' of four eruptive events producing explosions, pyroclastic flows, tall eruptive column >7 km above summit. Individual eruptive events occurred on 14th, 17th – 18th, 19th - 20th, and 23rd October. Volume estimates of air fall tephra deposits produced by eruptive cluster of 10th – 23rd October range from 0.157 km^3 to 0.4 km^3. Best estimate of volume of mapped pyroclastic flow deposits produced by eruptive cluster is 0.017 km^3. 14 October eruption consists of intense activity producing explosions, tall eruptive column, and pyroclastic flows in all barrancas. Stratospheric venting observed. Volume estimates of air fall tephra deposits produced by 14th October eruption range from 0.036 km^3 to 0.046 km^3. Largest of four eruptive events occurred on 17th – 18th October. Eruption on 19th – 20th October, generally considered to be smallest of four events, producing explosions and eruptive column (3 km above summit). Large eruption on 23rd October producing tephra column reaching to stratosphere, pyroclastic flows and extensive air fall, and ballistic fountaining to W, SW of summit.	Rose et al. (1978), Card 1967 (22nd October 1974) via GVP (2018), Rose et al. (2008), INSIVUMEH (2012), Escobar-Wolf (2013)
22 Feb – 3 Mar 1973	2	Eruption with summit explosions producing tall eruptive column and voluminous pyroclastic flows on SW, S, E flanks of Fuego. Best estimate of volume of mapped pyroclastic flow deposits produced by eruption is 0.015 km^3. Ash fall to 70 km distance to W, S, E.	Bonis & Salazar (1973), Rose et al. (1978), Escobar-Wolf (2013), Card 1583 (16th March 1973) via GVP (2018)

14 – 15 Sep 1971	4	Extremely large eruption producing large eruptive column (>10,000 m asl), ballistic fountaining (1000 m above summit crater) and pyroclastic flows in Barrancas Honda, Las Lajas, Ceniza. Reported as "most spectacular eruption in memory (at least 70 years)". Volume estimates of air fall tephra deposits produced by eruption range from 0.053 km^3 to 0.301 km^3.	Bonis & Salazar (1973), Rose et al. (1978), Escobar-Wolf (2013), Card 1296 (27th September 1971) via GVP (2018)
22 – 24 Apr 1967	2	Eruption producing eruptive column. Ash fall 40km from volcano.	Rose et al. (1978), Escobar-Wolf (2013)
12 – 13 Aug 1966	3	Large eruption producing ash and pyroclastic flows	Rose et al. (1978)
20 Apr – 1 May 1966	3	Large eruption with explosive activity producing ash and pyroclastic flows	Rose et al. (1978)
28 Sep – 1 Oct 1963	3	Large eruption with explosive activity from central crater. Pyroclastic flows in Barranca Honda. Seven deaths recorded from a secondary lahar.	BVE 4
9 Nov 1962	3	Large eruption with explosive activity producing eruptive column to 12 km asl. Ash fall recorded in Quetzaltenango, Huehuetenango and Coban, >100 km from Fuego	BVE 3, GVP (2018)
4 – 20 Aug 1962	3	Large eruption with explosive activity from summit crater producing lava effusion, eruptive column, pyroclastic flows in Barranca Honda. Lahars produced.	BVE 3, BVE 9-1, INSIVUMEH (2012)
19 – 21 Feb 1957	3	Large eruption producing tall tephra column and pyroclastic flows with accompanying surge. Best estimate of volume of pyroclastic flow deposits produced by eruption is 0.009 km^3. Ash fall recorded >100 km from Fuego.	Hantke (1955), Escobar-Wolf (2013)

9 – 13 Apr 1953	3	Large eruption producing (probable) pyroclastic flows in barrancas NE, NNE of Fuego. Best estimate of volume of lava produced by eruption is 0.022 km^3. Crater breach of 1932 completely filled.	Hantke (1955), Escobar-Wolf (2013)
Nov 1949 -	2	Eruption producing ash fall	Hantke (1955)
1 Dec 1944 -	2	Eruption producing ash fall in surroundings	Hantke (1959)
21 – 22 Jan 1932	4	Extremely large eruption producing large volume of tephra. >200 seismic events recorded on 21 Jan by seismograph in Guatemala City. Eruption column reaching >5000 m asl. Ash fall recorded >100 km from Fuego in El Salvador and Honduras. Breach in summit crater created towards NE. Summit crater excavated and greatly enlarged.	Escobar-Wolf (2013), Deger (1932)
Jan 10, 1896 -	2		GVP
28 Jun – 4 Jul 1880	4	Extremely large eruption producing eruptive column, ballistic fountaining, and (probable) pyroclastic flows on W and SW flanks. Ash fall recorded in departments of Mazatenango (>65 km) and Retalhuleu (>85 km).	Escobar-Wolf (2013), GVP (2018)
15 – 24 Sep 1860		Eruption producing eruptive column and lava.	Escobar-Wolf (2013)
18 Aug 1860		Eruption producing eruptive column, extensive ballistic fountaining, and lava descending S, SW flanks. Extensive damage to crops and road to coast reported.	Escobar-Wolf (2013)
17 Sep 1857 -	2	Eruption producing lava and ash. Ash fall reported in Guatemala City	Escobar-Wolf (2013)
16 – 18 Feb 1857		Large eruption producing large eruptive column (est. 620 m) and (probable) pyroclastic flows, descending SW, S and (minorly) N flanks.	Escobar-Wolf (2013)
9 – 11 Jan 1856	2	Eruption producing lava and ash. Ash fall reported in Tocoy and San Agustin Acasaguastlan (110 km).	Escobar-Wolf (2013), GVP
29 – 30 Sep 1855	2	Eruption producing large eruptive column	Escobar-Wolf (2013), GVP

1799? -		Unknown year; assigned 1799 by other authors. Eruption heating nearby streams.	Escobar-Wolf (2013)
May 1732	2	Eruption or series of eruptions over several days, producing rumbles and (probable) fire fountaining	Escobar-Wolf (2013), GVP
Sep 1730 -	2		GVP
Dec 1717 -	2		GVP
27 Aug – 29 Aug 1717	4	Extremely large eruption producing large eruptive column with volcanic lightning, rumbles, and (probable) pyroclastic flows. Most intense period of activity on 28th August. Observations of eruption reported in Izalco in El Salvador, >100 km from Fuego.	Escobar-Wolf (2013), GVP (2018)
14 Oct 1710 -	2	Eruption at night with various reports of incandescent fountaining and lava	Escobar-Wolf (2013), GVP
31 Jan – 2 Feb 1706		Eruption producing extensive ash (N.B. Records of 1706 eruption may be repetition of 1705 eruption)	Escobar-Wolf (2013), GVP
4 Oct 1705	2	Eruption producing ash	Escobar-Wolf (2013), GVP
31 Jan – 2 Feb 1705	2	Eruption producing extensive ash. Airfall of 7 – 8 cm (in Antigua Guatemala? 18 km).	Escobar-Wolf (2013), GVP
4 Aug 1702	2	Eruption producing lava and ash. Obscured daylight.	Escobar-Wolf (2013), GVP
1699 -	2		GVP
1686 -	2	Eruption producing ash. Notable lack of (probable) lava produced. Ashfall in Antigua.	Escobar-Wolf (2013), GVP
Sep 1685 -	2		GVP
1629 - 1632	2		GVP
Jan 1623 -	2	Eruption producing ash and (probable) pyroclastic flows	Escobar-Wolf (2013), GVP
1620 -	2		GVP

1617 -	3		GVP
1614 -	2		GVP
Jul 24, 1587 -	2		GVP
5 Dec 1581 – 15 Jan 1582	4	Extremely large eruption that heavily damaged community of San Pedro Aguacatepeque (7.4 km SE). Extensive ashfall in Antigua and reaching Pacific Ocean (>60km).	Escobar-Wolf (2013), GVP (2018)
Unknown – 31 Mar 1551	2		GVP
31 Dec 1531 -	2		GVP
30 Apr – 15 Jul 1524	2		GVP

Table 7.1: Table of notable eruptive events (VEI ≥ 2) at Volcán de Fuego in historic (16th – 20th century) and recent (1999 – present) periods

CHAPTER 8

APPENDIX C: TABLE OF MIROVA VALUES JAN 2015 - JUN 2018

Table of all MIROVA values >200MW at Fuego between January 2015 and June 2018, with associated dates and times. **Px no.** indicates any paroxysmal eruption coincident with the VRP value (1 – 41, beginning with Paroxysm 1 on 7th February 2015; see Table 2.1). **Bulletins** gives the number of selected INSIVUMEH special bulletins reporting on that paroxysm; bulletin details are placed next to VRP value closest to time of bulletin publication. (N.B. VRP datetimes are in UTC, INSIVUMEH bulletins are in local time; bulletins have been converted to UTC before matching to closest VRP value). Bulletins are selected to illustrate significant developments in activity e.g., declaration of start of a paroxysm, or descent of pyroclastic flows. **Title** and **Details** give, respectively, the title and the specific details of any special bulletins reporting on a paroxysmal eruption.

Year	No.	DateTime (UTC)	Value (MW)	Px no.	Bulletins	Title	Details
2015	1	08/02/2015 07:20	1423.30	1	008	Eruption	Paroxysmal eruption generating pyroclastic flows in Barrancas El Jute and Trinidad
	2	08/02/2015 16:45	918.65	1	015	Eruption	End of eruption at 10:00 local time on 8th February after 22 hours of activity.
	3	01/03/2015 04:50	480.50	2			
	4	01/03/2015 07:40	1206.00	2			
	5	01/03/2015 17:05	1034.17	2			
	6	01/03/2015 20:10	292.41	2			
	7	02/03/2015 03:55	869.50	2	025	Effusive eruption	Paroxysmal eruption beginning at 22:00 local time on 28th Feb produces incandescent fountains and lava flows in Barrancas Santa Teresa and Trinidad
	8	17/04/2015 16:20	673.03	3			
	9	17/04/2015 19:25	642.53	3			

10	18/04/2015 07:40	255.77	3			
11	18/04/2015 17:05	410.38	3	025	Effusive eruption	Eruption producing lava flow in Barranca Trinidad
12	11/05/2015 17:10	730.21				
13	06/06/2015 03:55	277.92	4	033	Eruption	Period of elevated activity in preceding weeks culminates in paroxysm beginning 6th June, with lava flows in Barrancas Santa Teresa and Trinidad
14	01/07/2015 16:05	3756.63	5			
15	01/07/2015 19:05	2968.09	5	054	Eruption	Paroxysmal eruption with explosions, ashfall, lava flow in Barranca Las Lajas, and pyroclastic flows
16	02/07/2015 04:35	418.40	5			
17	02/07/2015 07:20	354.20	5	055	End of eruption	5th paroxysmal eruption of 2015 ends
18	07/08/2015 04:10	277.47	6			
19	07/08/2015 16:20	300.74	6			
20	08/08/2015 07:40	493.75	6			

21	09/08/2015 16:10	2728.50	6	058	Effusive eruption	Gradual increase in activity since 1st August culminates in paroxysmal eruption on 9th August with lava flow in Barranca Las Lajas
22	09/08/2015 19:15	235.07	6			
23	10/08/2015 04:40	245.00	6	059	Effusive eruption	Paroxysmal eruption continues with explosions, avalanches, lava flow in Las Lajas
24	10/08/2015 07:25	511.83	6			
25	01/09/2015 16:15	2444.30	7	065	-	Heightened level of activity with frequent explosions and lava flow in Barranca Santa Teresa
26	01/09/2015 19:20	2081.12	7			
27	02/09/2015 07:30	2943.99	7	070	-	Paroxysmal eruption with incandescent fountaining feeding two lava flows in Barrancas Santa Teresa and Trinidad
28	27/09/2015 16:50	212.27				
29	08/10/2015 04:20	435.19	8			
30	11/10/2015 04:50	256.36	8	-	-	Lava flows in Barrancas Santa Teresa and Trinidad

31	11/10/2015 07:40	386.73	8			
32	11/10/2015 17:05	290.14	8			
33	12/10/2015 03:55	308.71	8			
34	12/10/2015 08:20	347.79	8	082	Increase in activity	Paroxysmal eruption maintained, with continued lava effusion
35	26/10/2015 04:10	357.01	9	087	Generation of pyroclastic flows	Paroxysmal eruption generating pyroclastic flows affecting flanks of volcano
36	27/10/2015 17:05	399.61	9			
37	09/11/2015 07:10	324.59	10			
38	09/11/2015 16:35	429.15	10	091	Increase in activity	Paroxysmal eruption generating lava flow in Barranca Las Lajas.
39	11/11/2015 04:10	865.77	10			
40	25/11/2015 19:35	232.68				
41	26/11/2015 05:05	476.99				
42	26/11/2015 07:50	231.14				
43	29/11/2015 08:20	824.62	11			

44	29/11/2015 16:10	446.39	11			
45	29/11/2015 19:15	1184.74	11			
46	30/11/2015 07:25	2132.39	11			
47	30/11/2015 16:50	1378.07	11			
48	30/11/2015 19:55	977.03	11	101	Eruption with pyroclastic flows	Large paroxysmal eruption generating lava flows in five barrancas (Ceniza, Honda, Las Lajas, Santa Teresa and Trinidad) and pyroclastic flows in Barranca Honda
49	01/12/2015 03:45	501.88	11	102	Eruption	Eruption decreasing in intensity
50	01/12/2015 08:10	266.12	11			
51	15/12/2015 03:55	335.26	12			
52	15/12/2015 16:10	338.57	12			
53	15/12/2015 19:15	278.57	12	105	Increase in activity	Increase in activity leading to paroxysmal eruption. Lava flows generated in Barrancas Santa Teresa and Trinidad
54	16/12/2015 04:40	589.27	12			

	55	16/12/2015 16:50	563.73	12			
	56	16/12/2015 19:55	290.19	12			
	57	17/12/2015 08:10	236.05	12			
	58	17/12/2015 19:00	209.09	12			
2016	59	02/01/2016 03:45	225.99	13			
	60	03/01/2016 04:25	423.08	13	001	Effusive eruption	Paroxysmal eruption generating lava flows in Barrancas Las Lajas and Trinidad
	61	03/01/2016 07:15	897.59	13			
	62	03/01/2016 16:40	1220.44	13	002	Effusive eruption	Paroxysmal eruption continues
	63	04/01/2016 07:55	807.14	13	003, 004	Effusive eruption; effusive eruption	Paroxysmal eruption continues with eruption plume to 7300m asl; eruption generating flows in Barrancas Las Lajas, Santa Teresa and Trinidad
	64	05/01/2016 04:15	261.15	13	006, 007	Eruption; decrease in energy of eruption	Eruption continues, with moderate pyroclastic flows generated in Barrancas El Jute, Las Lajas, and Trinidad; Eruption decreasing in energy 37 hours after onset

65	20/01/2016 07:55	563.63	14	008, 009 013	Increase in activity; effusive eruption	Increase in activity generating lava flows in Barrancas Las Lajas, Santa Teresa, and Trinidad; paroxysmal eruption with flows in barrancas maintained
66	21/01/2016 04:15	520.66	14	013, 016, 018	Pyroclastic flows and ash dispersal; eruption; end of eruption	Pyroclastic flows in Barrancas El Jute and Las Lajas; lava flows in Barrancas El Jute and Las Lajas; eruption ending after 24 hours of intense activity
67	08/02/2016 16:15	245.17	15			
68	09/02/2016 17:00	273.35	15	023, 024	Ash dispersal; eruption	Increased activity generating ash and lava flow in Barranca Las Lajas; paroxysmal eruption with lava flows in Barrancas Ceniza, Las Lajas, Trinidad
69	09/02/2016 20:00	256.00	15			
70	10/02/2016 16:05	6126.95	15	026	Eruption	Paroxysmal eruption with energy maintained for 12 hours and generating lava flows in Barrancas Las Lajas, Santa Teresa, and Trinidad

71	10/02/2016 19:05	1978.48	15	029	End of eruption	Eruption ends at 18:30 local time on 10th February
72	02/03/2016 04:05	4998.33	16	031, 034	Start of eruption; evolution of eruption	Paroxysmal eruption producing lava flow and pyroclastic flow in Barranca Las Lajas; increase in eruptive activity with extensive ash fall
73	02/03/2016 16:20	1540.30	16			
74	25/03/2016 16:25	230.19	17			
75	26/03/2016 07:45	408.92	17			
76	26/03/2016 17:10	257.09	17			
77	27/03/2016 04:00	2277.54	17	045	Eruption	Paroxysmal eruption with lava flows in Barrancas Ceniza, Las Lajas and Trinidad
78	12/04/2016 16:15	307.97	18	056	High level of activity	Paroxysmal eruption on 11th – 12th April producing incandescent fountaining and lava flows
79	12/04/2016 19:20	334.83	18			
80	13/04/2016 04:45	340.76	18			
81	13/04/2016 07:35	1993.77	18			

82	13/04/2016 16:55	782.71	18			
83	13/04/2016 20:05	284.43	18			
84	06/05/2016 04:50	437.38	19			
85	06/05/2016 07:40	899.26	19			
86	06/05/2016 17:05	1460.81	19			
87	07/05/2016 08:20	345.73	19			
88	22/05/2016 07:40	202.21	20	095, 097	Eruption with pyroclastic flows; eruption	Paroxysmal eruption generating pyroclastic flow in Barranca Las Lajas; eruption generating lava flow in Las Lajas
89	23/05/2016 19:15	476.61	20	099	End of eruption	Eruption ends at 12:40 local time on 23rd May
90	24/06/2016 16:10	347.75	21			
91	25/06/2016 04:40	523.75	21	114	Start of effusive eruption	Paroxysmal eruption begun with explosive activity and lava flows in Barrancas El Jute and Las Lajas
92	25/06/2016 07:25	591.47	21			

93	25/06/2016 16:50	393.50	21	118, 121, 123	Increase in activity; eruption; end of eruption	Paroxysmal eruption increasing in activity; paroxysmal eruption continuing after 24 hours of intense activity; eruption ends after over 30 hours of activity
94	27/07/2016 07:25	388.37	22			
95	29/07/2016 04:25	2442.92	22	134, 138	Strombolian eruption	Paroxysmal eruption begins at 05:45 on 28th July
96	29/07/2016 07:15	6974.17	22	138	Strombolian eruption	Paroxysmal eruption begins with Strombolian explosions and lava flows in Barrancas Las Lajas and Santa Teresa
97	29/07/2016 16:40	1101.81	22	141, 144	Eruption; end of eruption	Paroxysm continues with pyroclastic flow in Barranca Santa Teresa; paroxysm ends at 01:30 local time on 30th July after 44 hours
98	05/09/2016 16:05	808.42	23			
99	06/09/2016 16:45	302.54	23			
100	07/09/2016 18:55	587.13	23	169	Eruption	Paroxysmal eruption with lava flows in Barrancas Las Lajas and Taniluya
101	08/09/2016 04:20	204.63	23	171	Eruption	Eruption continues with moderate level of activity

102	26/09/2016 04:05	424.27	24			
103	26/09/2016 19:25	517.99	24			
104	27/09/2016 07:40	445.54	24	180, 182	Eruption; eruption	Increase in activity with lava flow in Barranca Las Lajas; paroxysmal eruption continues with lava flows in Barrancas Las Lajas and Santa Teresa
105	28/10/2016 04:05	218.18	25			
106	29/10/2016 07:40	497.42	25			
107	30/10/2016 16:10	1323.45	25	189	Eruption	Paroxysmal eruption continues with lava flow in Barranca Las Lajas
108	30/10/2016 19:10	645.46	25			
109	20/11/2016 04:15	288.27	26			
110	20/11/2016 07:00	313.24	26			
111	20/11/2016 16:25	1597.19	26			
112	20/11/2016 19:30	1336.67	26			

	113	21/11/2016 04:55	532.22	26	201		Paroxysmal eruption feeds lava flows in Barrancas Ceniza, Las Lajas, Trinidad and avalanches
	114	21/11/2016 07:45	1326.82	26			Activity ceases on 22nd November.
	115	20/12/2016 16:40	669.16	27			
	116	21/12/2016 07:55	2866.18	27	210, 212	Eruption; pyroclastic flows	Paroxysmal eruption feeding three lava flows in Barrancas Santa Teresa, Taniluya, Trinidad; pyroclastic flows reported in Barranca Taniluya
	117	22/12/2016 04:15	254.37	27			
2017	118	25/01/2017 04:00	308.15	28			
	119	25/01/2017 08:25	249.47	28			
	120	25/01/2017 16:15	1222.48	28	004	Increase in activity	Increase in eruptive activity, with incandescence feeding lava flow in Barranca Ceniza
	121	25/01/2017 19:20	1520.84	28			
	122	26/01/2017 07:30	1136.48	28			

123	26/01/2017 16:55	275.88	28	009	Eruption	Paroxysmal eruption with lava flows in Barrancas Ceniza and Trinidad
124	24/02/2017 16:25	549.47	29			
125	24/02/2017 19:30	715.28	29			
126	25/02/2017 04:55	1962.73	29			
127	25/02/2017 07:45	1246.59	29	020	Ash fall	Paroxysmal eruption with lava flows in Barrancas Ceniza, Las Lajas, Santa Teresa
128	25/02/2017 17:10	403.91	29			
129	01/04/2017 03:50	319.30	30			
130	01/04/2017 16:00	920.42	30			
131	01/04/2017 19:05	2531.27	30			
132	02/04/2017 04:30	1336.08	30	034	Eruption	Paroxysmal eruption producing lava flows in Barrancas El Jute and Las Lajas
133	02/04/2017 07:20	987.37	30			

134	04/05/2017 16:45	423.56	31	044; 046	Increase in activity; pyroclastic flows	Eruption with lava flow in Barranca Santa Teresa; paroxysmal eruption producing pyroclastic flows in Barrancas Las Lajas, Santa Teresa and Trinidad
135	06/06/2017 08:05	774.13	32	068	Descent of pyroclastic flows	5th paroxysmal eruption of 2017 continues with lava flow and pyroclastic flow generated in Barranca Santa Teresa
136	10/07/2017 07:50	331.90	33			
137	11/07/2017 16:20	4782.65	33	096, 097	Eruption	6th paroxysmal eruption of 2017 continues, generating lava flows in Barrancas Las Lajas and Santa Teresa; paroxysmal eruption continues
138	11/07/2017 19:25	525.93	33			
139	08/08/2017 16:45	295.31	34	105	Eruption begins	Paroxysmal eruption begins at 21:30 local time on 7th August with lava flows in Barrancas Ceniza and Santa Teresa
140	19/08/2017 04:15	276.16	35			
141	19/08/2017 16:25	310.64	35			

142	20/08/2017 07:45	731.70	35			
143	21/08/2017 04:00	742.79	35	127	Eruption	Paroxysmal eruption continues with lava flows in Barrancas Ceniza and Santa Teresa
144	14/09/2017 17:05	1733.03	36	148	Eruption	Paroxysmal eruption decreases in energy at 22:15 local time on 13th September. Lava flow in Barranca Santa Teresa produced
145	14/09/2017 20:05	884.67	36			
146	14/09/2017 20:10	702.81	36			
147	27/09/2017 19:35	713.82	37	154, 157	Eruption; end of eruption	Paroxysmal eruption producing lava flows in Barrancas Las Lajas and Santa Teresa; eruption ends at 21:00 local time on 28th September
148	03/11/2017 16:50	212.38	38			
149	05/11/2017 04:25	295.30	38			
150	05/11/2017 16:40	443.22	38	166	Increase in activity	Increase in activity with powerful incandescent fountaining
151	05/11/2017 19:45	227.32	38			

	152	06/11/2017 07:55	350.12	38	170, 175	Eruption; end of eruption	Paroxysmal eruption begins at 19:30 local time on 5th November with lava flows in Barrancas Ceniza and Santa Teresa; eruption ends at 07:00 local time on 7th November
	153	10/12/2017 04:55	625.00	39			
	154	10/12/2017 07:45	366.51	39			
	155	10/12/2017 17:10	1766.86	39	182	Eruption begins	Paroxysmal eruption begins at 17:50 local time on 10th December, with lava flow in Barranca Santa Teresa
	156	12/12/2017 04:45	314.05	39	187	Eruption ends	Eruption ends at 06:50 local time on 12th December
2018	157	31/01/2018 19:50	215.11	40			
	158	01/02/2018 08:05	1334.75	40	005	Eruption	Paroxysmal eruption begins at 21:25 local time on 31st January, with lava flows in Barrancas Honda, Las Lajas and Santa Teresa
	159	01/02/2018 18:55	2239.39	40	011	Eruption ends	Paroxysmal eruption ends after 20 hours. Pyroclastic flows generated in Barrancas Honda, Las Lajas, Santa Teresa, Trinidad

160	02/02/2018 04:20	470.76	40			
161	16/04/2018 19:30	304.26				
162	12/05/2018 07:40	398.50				
163	21/05/2018 04:45	334.22				
164	22/05/2018 08:15	451.98				
165	29/05/2018 08:20	261.31				

	166	03/06/2018 16:30	242.17	41	027, 030, 033, 036	Eruption with pyroclastic flows; eruption with pyroclastic flows in Barrancas Ceniza and Santa Teresa, ash above the capital city; end of eruption; descent of pyroclastic flows	Paroxysmal eruption generating pyroclastic flows in Barranca Santa Teresa; largest eruption of recent years generating pyroclastic flows in Barrancas Ceniza, Honda, Las Lajas, Santa Teresa, Taniluya; eruption ending after 16 hours with last pyroclastic flow generated at 16:45 local time on 3rd June; descent of pyroclastic flows in Barrancas El Jute and Las Lajas at 14:10 local time on 5th June

CHAPTER 9

APPENDIX D: QUESTIONNAIRES

This fourth appendix contains the questionnaires that guided the fieldwork I undertook in 2019 to provide results of Chapter 3. Questionnaires appear first in English, then Spanish. Note that while the questionnaire includes "risk perception" as a central theme, I do not include this in Chapter 3.

9.1 Questionnaire (English)

Questionnaire for study participants who are residents of communities close to Volcán de Fuego. The research questions which I wish to answer:

1. ¿Has the change in eruptive pattern (presented in Chapter 2) been reflected in perceptions of activity among people who live close to Fuego?
2. Is perception of volcanic activity considered by these people as a significant factor in the decision to evacuate in the new eruptive regime?

Guiding papers for questionnaire design:

- Stone et al. (2014) Risk reduction through community-based monitoring: the vigías of Tungurahua, Ecuador
- Johanesdottir & Gisladottir (2010) People living under threat of volcanic hazard in southern Iceland: vulnerability and risk perception
- Van Manen (2014) Hazard and risk perception at Turrialba volcano (Costa Rica): implications for disaster risk management

- Nunes Correia et al. (1998) Flood Hazard Assessment and Management: Interface with the Public

Theme	**Question**	**Additional questions**	**Reason(s) for asking**
Socio-demographic	Age, sex, location, occupation, level of education		Provides context
Home, family, and friends	How many people live in your home? For how long have you lived in this community? Why did you choose to live here?	Have you considered moving elsewhere in future? Why/why not?	Provides context; consideration of vulnerability or resilience (length of time living in community)
Livelihood	What is a typical day for you? How do you maintain a living?		Provides context; consideration of vulnerability or resilience
Environment	What are the main problems or hazards in your community?		Prominence of different hazards; determine if volcano is identified as a hazard
Activity	What happens before an eruption of Fuego? Are there any signals before an eruption? What does the volcano do when it is active? What do you see, hear, feel?		Gives individual perceptions of volcanic activity; allows the participant to express themselves in their own words
Activity – frequency	In the time that you have lived here, how many eruptions of Fuego can you remember? Have you seen any change in the volcano's activity in recent years?		Consideration of perceptions and experiences; determines if participant has seen similar changes to those presented in Chapter 2
Hazard	How do you know if the volcano is an imminent danger? If the volcano became dangerous, what would you do?		Hazard perception; risk perception; comparison between sites

Good	Is there any benefit or good the volcano gives to your community?		Perception of the volcano
Memory	What did your grandparents say or tell you about the volcano? Have you heard any stories about Fuego?	Could you describe them to me?	Collective memory y folklore
Evacuation	Have you ever had to evacuate because of the volcano's activity? Would you evacuate from volcanic activity in future? Why/why not?	Have you ever wanted to evacuate because of the volcano's activity, but were not able to do so?	Risk perception and response; comparison between sites
Confidence	Have you received any talk or training related to Fuego? What do you know about the work that INSIVUMEH/-CONRED does?		Relationship with institution (confidence); comparison between sites

9.2 Questionnaire (Spanish)

Cuestionario para participantes que vienen de comunidades ubicadas cerca al Volcán Fuego. Las preguntas científicas que quiero preguntar:

1. ¿El cambio en patrón eruptivo (presentado en Capitulo 2) ha sido reflectado en las percepciones de actividad entre las personas que viven cerca a Fuego?
2. ¿La percepción de actividad volcánica es importante para estas personas? ¿Y como influencia esta percepción en decisiones en relación con la evacuación este periodo de actividad?

Tema	**Pregunta**	**Preguntas siguientes**	**¿Por qué esta pregunta?**
Socio-demográfico	Edad, sexo, ubicación, trabajo, nivel de educación		Da contexto

Hogar, familia, amigos	¿Cuántas personas viven en su hogar?¿Por cuánto tiempo ha vivido en esta comunidad? ¿Por qué eligió usted vivir aquí?	¿Ha contemplado mudarse de la zona en el futuro? ¿Por qué/por qué no?	Da contexto; consideración de resistencia o vulnerabilidad (largo de tiempo viviendo en su lugar)
Sustento	¿Cuál es su actividad cotidiana? ¿Qué hace usted para mantenerse?		Da contexto; consideración de resistencia o vulnerabilidad
Ambiente	¿Cuáles son los problemas o amenazas en su comunidad?		Prominencia de amenazas diferentes; prueba si el volcán se identifica como amenaza
Actividad	¿Qué pasa antes de una erupción de Fuego? ¿Hay algunas señales antes de una erupción? ¿Qué hace el volcán cuando esta activo? ¿Qué es lo que siente, ve, escucha, usted?		Da percepciones individuales de actividad volcánica; permite el participante expresarse en sus propias palabras
Actividad – Frecuencia	Durante el tiempo que ha vivido aquí, ¿cuántas erupciones de Fuego puede recordar usted? ¿Ha visto usted algún cambio en la actividad del volcán en los últimos años?		Consideración de percepciones; prueba si el participante ha visto los cambios marcados en Capitulo Dos
Amenaza	¿Cómo sabe usted si el volcán representa un peligro inminente? Si el volcán se vuelve peligroso, ¿que haría usted?		Percepción de amenaza; percepción de riesgo; comparación entre lugares
Bueno	¿Hay algún beneficio que el volcán de a su comunidad?		Percepción del volcán

Memoria	¿Qué le contaron o dijeron sus abuelos sobre el volcán? ¿Usted ha escuchado alguna historia sobre Fuego?	¿Me lo podría describir?	Memoria colectiva y folklore
Evacuación	¿Ha tenido usted que evacuar alguna vez por actividad del volcán? ¿Usted evacuaría por actividad del volcán en el futuro? ¿Por qué/por qué no?	En alguna ocasión, ¿quiso evacuar por la actividad del volcán, pero no pudo?	Percepción de riesgo y respuesta; comparación entre lugares
Confianza	¿Usted ha recibido alguna charla, capacitación o formación sobre Fuego? ¿Qué conoce usted acerca del trabajo que realiza INSIVUMEH/CONRED?		Relación con instituto (confianza); comparación entre lugares

CHAPTER 10

APPENDIX E: ADDITIONAL RESULTS FROM TRANSCRIPT CODING

This appendix contains results from coding interview transcripts. Initial results using NVivo in-house analytical tools appear before a mind-map I created to summarize main themes found through iterative coding of 2019 transcripts.

10.1 Assorted Results

FIGURE 10.1. Word cloud for 2018 fieldwork generated from word frequencies in transcripts. Cloud generated from NVivo's in-house tools and filtered to remove "filler" words including prepositions and articles.

FIGURE 10.2. Word cloud for 2019 fieldwork generated from word frequencies in transcripts. Cloud generated from NVivo's in-house tools and filtered to remove "filler" words including prepositions and articles.

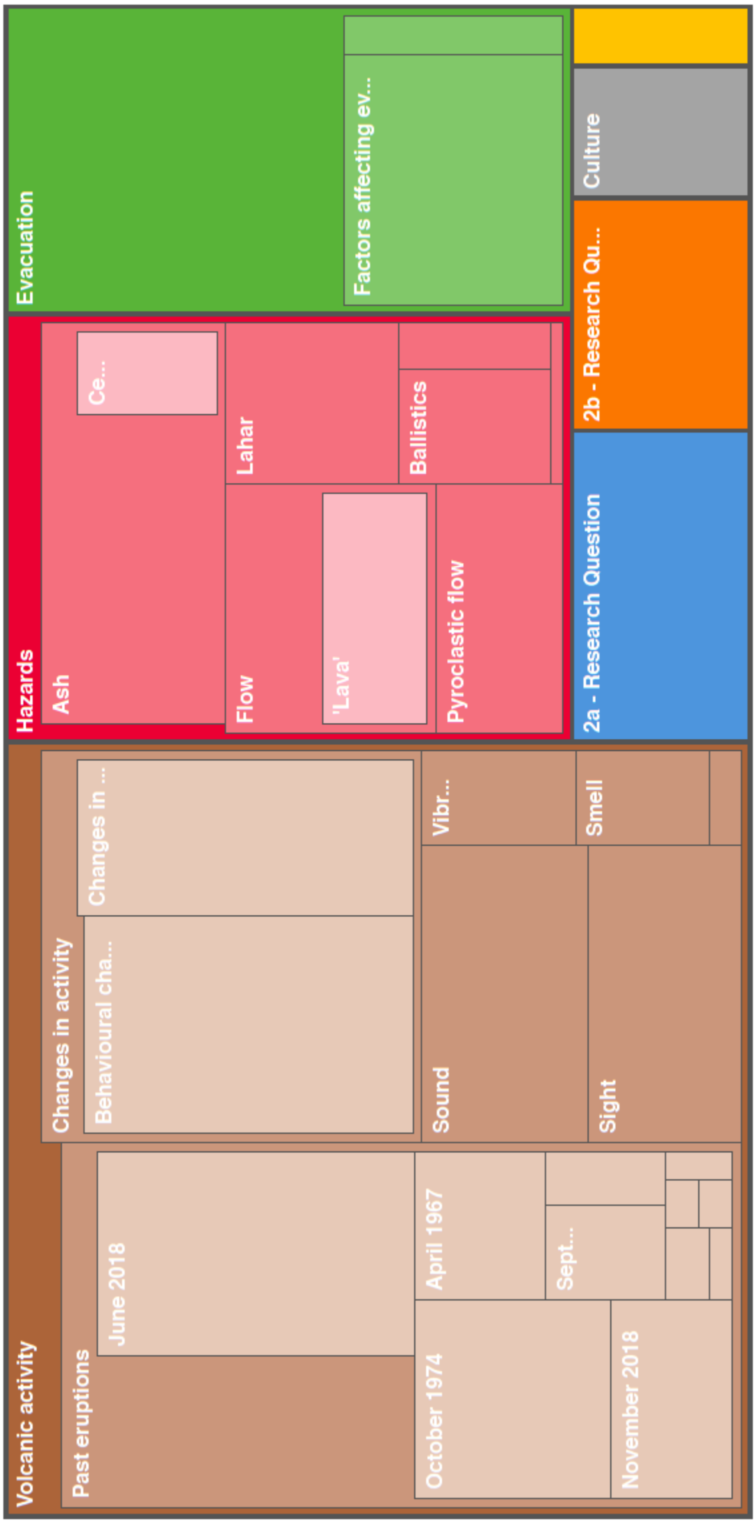


FIGURE 10.3. An NVivo visualization of code hierarchies created from coding of transcripts from 2019 fieldwork. Each colour relates to a different ’parent’ code that contains multiple ’children’ subcodes. For example, ’Hazards’ is a parent code that contains children codes of ’ash’ and ’ballistics’.

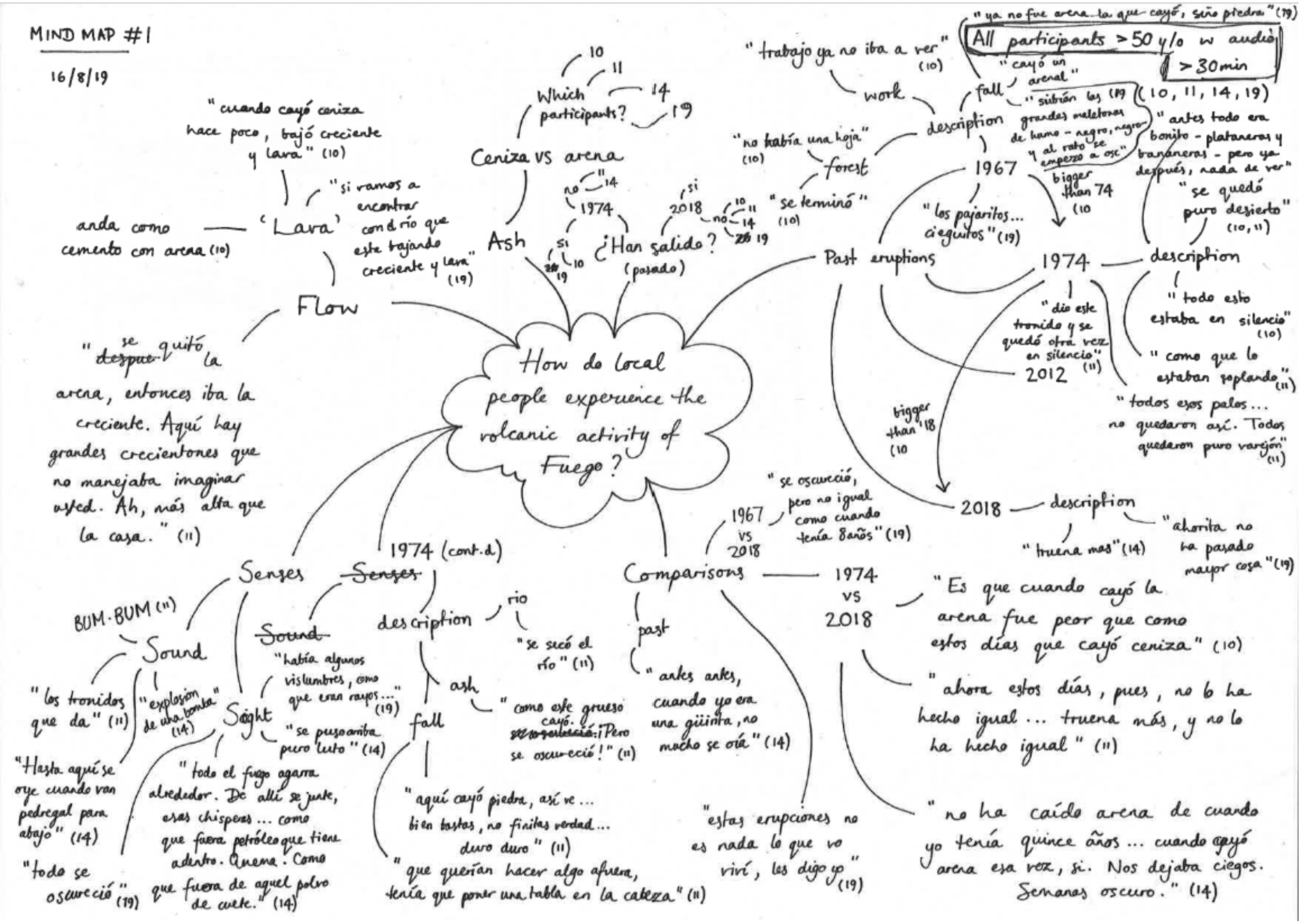


FIGURE 10.4. A hand-drawn mind-map of the main themes discovered through iterative coding sessions of interview transcripts from 2019 fieldwork season. Numbers relate to the interview transcript number. Quotations are verbatim.

CHAPTER

11

APPENDIX F: PYTHON SCRIPT FOR FILTERING CLOUDY AND CLEAR IMAGES

This is a script written in the Python programming language that processes a series of .png images of Volcán de Fuego to distinguish those that show its summit and those that contain a cloudy summit.

```
# -*- coding: utf-8 -*-
"""
Created on Wed Aug  8 12:34:11 2018

@author: an16975
This is a simple script that loops over a series of images in a folder,
draws a series of three transects on the image, calculates the line of best fit for the
scatter plot of pixel values across each transect, returns the gradient of each line
of best fit, and then separates 'clear' images from 'cloudy' according to a Boolean
threshold (here if any of the three gradients of line of best fit is greater than 0.4).
Magic!
"""
##Import modules
import cv2
import numpy as np
import os, os.path
import pandas as pd
import matplotlib.pyplot as plt
import time

##Specify filepath to images
```

```python
imageDir = '/Volumes/APRIORI_ASH/Guatemala/Guatemala Campaign June 2018/lazarus/Fuego_IR/png/2018/181'
image_path_list = [] #create empty list
valid_image_extensions = ['.png'] #valid extension is png only
valid_image_extensions = [item.lower() for item in valid_image_extensions] #catches all uppercase file extensions

##Calculate time to execute script
start = time.time()

##Create a list for all files in directory and append all files with valid extension
for file in os.listdir(imageDir):
    extension = os.path.splitext(file)[1]
    if extension.lower() not in valid_image_extensions:
        continue
    image_path_list.append(os.path.join(imageDir, file))

##Create a list for all images that will be sorted as 'clear' images
clear_list = []
cloudy_list = []

##Start window thread - necessary to prevent screen freeze
cv2.startWindowThread()

##Loop through image_path_list to open each image
for imagePath in image_path_list:
    image = cv2.imread(imagePath, 0)
    ##Catch any null images
    if not image is None:

        ##Create transects
        #draw line formula: cv2.line(image,(x1,y1),(x2,y2),(r_value,g_value,b_value),thickness)
        #image co-ordinates start at (0,0) in top-left corner
        line_1 = cv2.line(image,(275,225),(275,325),(0,0,0),1)
        line_2 = cv2.line(image,(300,225),(300,325),(0,0,0),1)
        line_3 = cv2.line(image,(400,225),(400,325),(0,0,0),1)
        pixels_1 = line_1[275, 225:325]
        pixels_2 = line_2[300, 225:325]
        pixels_3 = line_3[400, 225:325]
        #print(pixels_1.shape)
        x_axis = np.arange(225, 325, 1)

        ##Draw scatter plots of pixel values across each image transect (optional)
        #plt.scatter(x_axis, pixels_1, s=8, c='b', label='line_1')
        #plt.scatter(x_axis, pixels_2, s=8, c='r', label='line_2')
        #plt.scatter(x_axis, pixels_3, s=8, c='g', label='line_3')
        #plt.legend()
```

```
        #plt.show()

        ##Find slope and intercept of line of best fit for each plot
        slope_1, intercept_1 = np.polyfit(x_axis, pixels_1, 1)
        slope_2, intercept_2 = np.polyfit(x_axis, pixels_2, 1)
        slope_3, intercept_3 = np.polyfit(x_axis, pixels_3, 1)
        #print('Slope 1 is', slope_1)
        #print('Slope 2 is', slope_2)
        #print('Slope 3 is', slope_3)
        #sum_slopes = slope_1 + slope_2 + slope_3
        #print('Sum of slopes is', sum_slopes)

        ##Create 'if' statement to distinguish clouds from clear images
        if (np.average(pixels_3) < 150): #(slope_1 < 0.1) or (slope_2 < 0.1) or (slope_3 <
        ↪  0.1):
            #print('Image is clear', imagePath)
            clear_list.append(1)
            cloudy_list.append(0)
        else:
            #print('Image is cloudy')
            clear_list.append(0)
            cloudy_list.append(1)

        ##Show image with imshow() (optional)
        #waitkey() wait time is required to display image
        #0 = wait indefinitely, 3000 = wait 3 seconds
        #cv2.imshow('Image', image)
        #time.sleep(2)
        #cv2.waitKey(2000)

        ##Close window (optional)
        #plt.close()
        #cv2.destroyAllWindows()

##Print total number of clear-sky images in test set
print('Total number of clear images is', sum(clear_list))

"""
##Print all files in directory
for root, dirs, file in os.walk(imageDir):
    for name in file:
        if name.endswith('.png'):
            print(name)

##Create CSV file with all results from cloudy/clear test
test_list = pd.DataFrame({'filename': name,'clear': clear_list,'cloudy': cloudy_list})
test_list_2 = pd.DataFrame({'real_filename': file})
#print(test_list)
```

```
outDir = '/Users/an16975/Desktop/PhD/Code/IR Camera/Cloud/True Images_03/2017/310/310_5/'
test_list.to_csv(outDir+'clear-cloud_test_output.csv')
test_list_2.to_csv(outDir+'real_filename_output.csv')
"""

#Calculate time to execute script
end = time.time()
print(end - start, 'seconds')
```

CHAPTER 12

APPENDIX G: PYTHON SCRIPT FOR PROCESSING SO2 FLUXES FROM NICAIR IMAGES

This is a script written in the Python programming language that takes NicAIR images as input files and produces images of SO_2 stacked column density (SCD) as outputs.

```
# -*- coding: utf-8 -*-
"""
Created on Mon Jan 08 10:29:27 2018

@author: glhet

CODE DEVELOPED BY HELEN and edited by Ailsa

Makes SO2 images from NicAIR calibrated images
"""

##IMPORT MODULES
import os
import glob
import numpy as np
from astropy.io import fits
import warnings
from astropy.utils.exceptions import AstropyWarning
import math
import matplotlib.pyplot as plt
from scipy.ndimage.filters import median_filter
```

```
22  import array
23  import matplotlib.image as mpimg
24  import datetime
25  import matplotlib.colors as mplcol
26  import time as t
27
28  #start timer
29  startTime = t.time()
30
31  #turn off matplotlib interactive mode
32  plt.ioff()
33
34  """
35  WHEN YOU SEE A COMMENT LIKE THIS, CHECK YOU HAVE FOLLOWED INSTRUCTIONS WITHIN!
36  """
37
38  ################################################################################
39
40  ##DIRECTORIES
41  #location of the raw data
42  """
43  CHANGE DIRECTORY AND CHECK YOU ARE NOT CLOBBERING!!!
44  """
45  in_dir = "/Users/an16975/Desktop/PhD/Code/IR Camera/Helen Google Drive/04_Real
    ↪  Runs/2017_307_ovfgo/00_RAW/"
46  #location where you want images saved - check they are in place
47  out_dir= "/Users/an16975/Desktop/PhD/Code/IR Camera/Helen Google Drive/04_Real
    ↪  Runs/2017_307_ovfgo/01_SO2_Output/"
48  out_dir_T = out_dir+"Ts/"
49  out_dir_TD = out_dir+"TDs/"
50  out_dir_OD = out_dir+"ODs/"
51  out_dir_so =  out_dir+"SOs2/"
52  #out_dir_hist = out_dir+"Histograms/"
53
54
55  ##CREATE MASK
56  #mask files can be used to mask out the land, which can look better
57  #you can make them in envi using the ROI tool (see text file) or you can make it using a
    ↪  threshold in python.
58  """
59  CHECK MASK MATCHES VIEWPOINT!!!
60  """
61  maskfile =  in_dir+'/mask-ovfgo.png'     #specify location of mask file
62  msk = mpimg.imread(maskfile)             #read mask file
63  msk[msk==0] = None                       #convert B/W of mask file to 0/1
64  msk[msk==255] = 1.
65  msk = msk[40:240, 40:240]                #crop mask to same dimensions of so2 image (found at
    ↪  line 251, if subsetting)
```

```python


##WIND SPEEDS
#Note: try to find actual wind speeds for your data times!
#Try wunderground.com or timeanddate.com
windspeedsfile = in_dir+'/windspeeds_ailsa-bash-2_output.txt'   #specify windspeed locns
numps = np.loadtxt(windspeedsfile, dtype='str')
#load windspeeds as series of strings
#(3xn array with rows: 'image filenamebase', 'windspeed1', 'windspeed2' x n)


##FLUXES
#create text file with output headings
the_file = open(in_dir+'/fluxes.txt', 'a')             #open new text file in append mode
the_file.write('Time'+'\t'+'Emmrate'+'\t'+'ERvertline'+'\t'+'Windspeed'+'\t'+'FPA Temp'+'\n')
#write tab-delimited headings: Time, Emission Rate, Emission Rate Vertical Line, Windspeed, Focal Plane Array Temp


##COLOUR SCHEME
#Optional. To use a colour scheme generated to be similar to IDL 22.
col_file = in_dir+'/freds_colors_FINAL_ailsa-bash.ctb'      #specify location of colorscale file
colors = np.loadtxt(col_file)                               #load colorscale file as 'colors'
colors = np.reshape(colors,(-1,3))                          #reshape array. -1 specifies we do not know one dimension of new array. 3 specifies we want new array in 3 columns.
name = ' '                                                  #name your colourmap
cmap = mplcol.ListedColormap(colors,name)                   #make colourmap from list of colours: colour list is .ctb file, name is '   '


##########################################################################################

"""
CHECK CAMERA PARAMETERS (Carameters?) ARE CORRECT FOR THE DATA CHUNK YOU ARE PROCESSING!
Camera parameters affect pixel dimensions.
"""

##CAMERA PARAMETERS
#will be different for each day of processing
camD = 7.4                  #the distance in km from camera to the volcano
camA = 20.                  #the angle above horizontal of camera pointing
fov = [18.,14.5]            #the camera HALF FOV in degrees (25mm lens gives 35.5 x 28.7 fov)
n_cols = 644                #number of pixels in x-direction (for 644x512 image)
n_rows = 512                #number of pixels in y-direction (for 644x512 image)


##PIXEL DIMENSIONS
```

```
#calculate pixel dimensions based on camera parameters
pix_w = (2*math.tan(math.radians(fov[0])) * camD * 1000.) /n_cols       #width of pixel
↪   (calculated from camera distance from summit using Pythagoras)
camtopl = camD / math.cos(math.radians(camA))                           #vertical HALF height
↪   of image from camera angle and distance in km, using Pythagoras
pix_h = (2*math.tan(math.radians(fov[1])) * camtopl * 1000.) /n_rows    #height of pixel


##NEW DIRECTORIES
#check: if following directories do not exist, create them
if not os.path.exists(out_dir_T):           #if it don't exist,
    os.makedirs(out_dir_T)                  #make new Temp directory
if not os.path.exists(out_dir_TD):          #if it don't exist,
    os.makedirs(out_dir_TD)                 #make new Temp Diff directory
if not os.path.exists(out_dir_OD):          #if it don't exist,
    os.makedirs(out_dir_OD)                 #make new Optical Depth directory
if not os.path.exists(out_dir_so):          #if it don't exist,
    os.makedirs(out_dir_so)                 #make new SO2 directory.


##CHANGE FILE EXTENSION
#change extension of files in input directory to .fits (if not already)
old_ext = '.raw'                            #specify old file extension as .raw
new_ext = '.fits'                           #specify new file extension as .fits
os.chdir(in_dir)                            #change current directory to in_directory
files = os.listdir(in_dir)                  #returns list (in arbitrary order) of all files in
↪   in_dir and stores them in 'files'
for filename in files:
    file_ext = os.path.splitext(filename)[1]
    if old_ext == file_ext:
        newfile = filename.replace(old_ext, new_ext)
        os.rename(filename, newfile)


##FILES LIST
#makes two lists, of image files and calibration files
files_list = sorted(glob.glob(in_dir+"/*1s.fits"))       #make list of 's.fits' files (aka
↪   open-shutter files) in input directory using glob
#files_list = files_list[0]  #remove this line later
cals_list = sorted(glob.glob(in_dir+"/*1r.fits"))       #make list of 'r.fits' files (aka
↪   closed-shutter, calibration files)


##START LOOP
#Iterative loop that generates an SO2 image for each shutter-open image in folder
for fname in files_list:

    ##CREATE IMAGE FILES LIST
```

```
    #Generate list of all 4 files in the same subset
    #fname = files_list
    fnamelist = []
    fnamebase = fname.split("s.fits")[0][0:-1]      #create base filename from .fits file in
     ↪  directory
    fname1 = fnamebase+"1s.fits"                    #create list of files with "1s.fits" and
     ↪  append "1s.fits" to base filename

    if os.path.exists(fname1) == True:              #if a file exists with "fname1" and
     ↪  extension "1s.fits",
        fnamelist.append(fname1)                    #append that file to list "fnamelist"
    fname2 = fname1.replace('1s.', '2s.')           #create list of files with "2s.fits"
    if os.path.exists(fname2) == True:              #if file already exists with basename and
     ↪  extension "1s.fits",
        fnamelist.append(fname2)                    #append second file with same basname to
         ↪  list with "2s.fits" extensions
    fname3 = fname1.replace('1s.', '3s.')           #same process with "3s.fits"
    if os.path.exists(fname3) == True:
        fnamelist.append(fname3)
    fname4 = fname1.replace('1s.', '4s.')           #same process with "4s.fits"
    if os.path.exists(fname4) == True:
        fnamelist.append(fname4)


    ##CREATE CAL FILES LIST
    #find cal files closest to image files & read in
    calbases = []
    for cfiles in cals_list:
        calbases.append(float(cfiles.split("r.fits")[0].split("/")[-1]))

    fbase = float(fnamebase.split("/")[-1])

    ##MATCH CAL FILES TO IMAGE FILES
    diffs = []                                      #create new list "diffs"
    for cbs in calbases:                            #for each cal file (aka value in list
     ↪  "calbases"),
        diffs.append(np.abs(cbs - fbase))           #find the nearest image file (value in
         ↪  list "fbase") and append the difference between two files to list "diffs"
                                                    #difference is float values of filenames
    cname1 = cals_list[np.argmin(diffs)]            #create variable "cname1". Use 'argmin' to
     ↪  find index of minimum value within 1D-array "diffs". Append cal file that corresponds
     ↪  to this index to list "cname1".
    cnamelist = []                                  #create new list "cnamelist"
    if os.path.exists(cname1) == True:              #if you have a cal file with extension
     ↪  "1r.",
        cnamelist.append(cname1)                    #append to new list
    cname2 = cname1.replace('1r.', '2r.')           #create variable "cname2".
    if os.path.exists(cname2) == True:              #if cal file with extension "1r." exists,
```

```
        cnamelist.append(cname2)                      #append next cal file to variable
        ↪  "cname2".
    cname3 = cname1.replace('1r.', '3r.')
    if os.path.exists(cname3) == True:
        cnamelist.append(cname3)
    cname4 = cname1.replace('1r.', '4r.')
    if os.path.exists(cname4) == True:
        cnamelist.append(cname4)


    #now we have two lists - fnamelist and cnamelist which contain the sets of the files for
    ↪  the raw data and the calibration files.
    warnings.simplefilter('ignore', category=AstropyWarning)  #suppresses all warnings, to
    ↪  avoid problems

    """
    CALIBRATION COEFFICIENTS - Specific to each instrument
    It is ABSOLUTELY critical that the cal coefficients are correct.  Cal coefficients change
↪  over time
    for each instrument and are instrument specific.  Cal also changes wrt FPA T, so if the
↪  FPA T
    is different from that used during calibration then the calibration coefficients are
↪  unlikely to be valid.
    """

    ##CALIBRATION COEFFICIENTS for NicAIR [Purple cam, OVFGO on 03/11/2017]
    wav = 10000./8.65,10000./10.00,10000./10.87,10000./12.00       #wavenumbers of filters
    beta = -17.513,-28.218,-26.444,-35.207                          #possibly ... gain for each
    ↪  channel for specified environmental conditions?
    alpha = 0.427,0.085,0.647,0.844                                 #possibly ... offset for
    ↪  each channel for specified environmental conditions?
    LM = 1.257,1.297,1.242,1.287                                    #UNKNOWN. ... Lagrange
    ↪  multiplier???
    img_offsets = 0.,0.,-5,0.                                       #derived later due to
    ↪  calibration error, ideally 0.


    ##PLANCK FUNCTION CONSTANTS
    c1 = 1.19104e-5                                                 #UNKNOWN. ... variable used
    ↪  for later inversion of Planck function.
    c2 = 1.43877                                                    #UNKNOWN. ... variable used
    ↪  for later inversion of Planck function.

    tim = []                                                        #create new list 'tim'
    datheaders = []                                                 #create new list
    ↪  'datheaders'

    ##READ CAL FILES
```

```
    #read in and calibrate files
    for i in range(0, len(fnamelist)):                             #for each file in
    ↪   "fnamelist"
        fhduz = fits.open(fnamelist[i],ignore_missing_end=True)    #open image file, don't
        ↪   issue exception if file is missing END card in last header. See
        ↪   http://docs.astropy.org/en/stable/io/fits/
        fhdu = fhduz[0]                                            #variable "fhdu" is first
        ↪   card (1st element of array) in image file
        idat = fhdu.header['SDAT']                                 #date, from contents of
        ↪   fits header object called "SDAT"
        tcal = np.mean([float(fhdu.header['TBB1']), float(fhdu.header['TBB2']),
        ↪   float(fhdu.header['TBB3']), float(fhdu.header['TBB4'])])        #calibrated temp
        ↪   calculated from mean of 4 blackbody temps
        tfpa = fhdu.header['TFPA']                                 #temperature of focal plane
        ↪   array, from card with header "TFPA"
        if tcal == 0:                                              #if calibrated temperature
        ↪   is zero,
            tcal = fhdu.header['TFPA']                             #get cal temp from focal
            ↪   plane array T.
            if tcal == 0:                                          #if focal plane array T
            ↪   still zero (and therefore cal T too),
                tcal = 295.0                                       #designate cal T as 295K.

        #save the first header for later
        datheaders.append(fhdu.header)

        fim = fhdu.data                                            #append image data to
        ↪   variable "fim"
        fhduz.close()                                              #close image file

        chduz = fits.open(cnamelist[i],ignore_missing_end=True)    #open cal file, don't issue
        ↪   exception if file is missing END card in last header.
        chdu = chduz[0]                                            #variable "chdu" is first
        ↪   card (1st element of array) in cal file
        cim = chdu.data                                            #append calibrated file
        ↪   data to variable "cim"
        chduz.close()                                              #close calibration file

        """
        WHAT DOES THIS BIT BELOW DO??? (IDEA: Gets calibrated radiance values from calibrated
↪   T values of image)
        """
        rcal=c1*wav[i]**3/(math.exp(c2*wav[i]/tcal)-1)             #similar to, but not same
        ↪   as, Planck Function expressed on pg. 15 of Thompson & Watson (2015) or
        ↪   https://aip.scitation.org/doi/pdf/10.1063/1.4903034
        z1=c1*wav[i]**3                                            #float 'rcal' is possibly
        ↪   calibrated radiance (ref radiance?)
        z2=c2*wav[i]
```

```
        rimg=(beta[i] + alpha[i]*(fim-cim) + LM[i]*rcal)          #array 'rimg' is radiance
        ↪ values of each pixel in image. A 2D array (of 644x512 pixels)

        """
        DO YOU WANT TO SUBSET IMAGE?
        """
        ##SUBSET IMAGE
        #Change image region to desired area (if necessary) OR comment out.
        rimg=rimg[40:240, 40:240]                                #if subsetting image, array
        ↪ 'rimg' is resized to a 2D array of ww x zz pixels (depending on the co-ordinates
        ↪ you specify on this line)
        rim= z2/(np.log(z1/rimg+1.0))
        timg=rim+img_offsets[i]
        tim.append(z2/(np.log(z1/rimg+1.0)))


    ##SAVE FILES
    #save T-calibrated files in all 4 channels.
    outfile = out_dir+str(int(fbase))+'_calibrated.fits'                          #change
    ↪ filepath to where you want image saved, and change filename as appropriate
    #initiate the hdu list with the first image, and also the primary hdu
    hdulist = fits.HDUList(fits.PrimaryHDU())#, fits.CompImageHDU(data=tim[0],
    ↪ header=datheaders[0],compressionType='HCOMPRESS_1'))

    ##FILL LIST
    #populate the list with the remainder of the data
    nimages=len(tim)                                                              #integer
    ↪ 'nimages' is number of images aka length of list 'tim'
    for u in range(0,int(nimages)):                                               #for each
    ↪ element in 'nimages',

        ↪ hdulist.append(fits.CompImageHDU(np.asarray(tim[u]),datheaders[u],compressionType='HCOMPRESS_1')
        ↪ #append calibrated temperatures, date headers to .fits files, compress files
        hdulist[u].header['OBSUNIT'] = 'Post Calibrated BTs'
        ↪ #append string "Post-Calibrated BTs" to header rows of .fits files, so you know
        ↪ that they have been calibrated
        hdulist.writeto(outfile, clobber=True )
        ↪ #write list of HDUs (Header Data Unit) in data. Clobber overwrites file, so you
        ↪ will update list as you iterate over files


    ##REMOVE NOISE
    tim86 = median_filter(tim[0], 5)          #apply median filter to images for 8.6 filter,
    ↪ 1st column of array in "tim". median_filter takes inputs (input_array, window_size)
    ↪ where 'window_size' is size of window across which to select median pixel.
    #tim10 = median_filter(tim[1], 5)         #apply median filter to images for 10 filter, 2nd
    ↪ column of array
```

```
    tim11 = median_filter(tim[2], 5)         #apply median filter to images for 11 filter, 3rd
    ↪  column of array in "tim". For Lazarus, using third filter
    #timbb = median_filter(tim[3], 5)        #apply median filter to  images for broadband
    ↪  filter, 4th column of array


    ##REPLACE NAN VALUES IN TEMP ARRAYS!
    #Replace NaN values in TempArray in Channel 11 (from
    ↪  'so2maker_ailsa-bash_triple-plot_2.py')
    #tim11[np.isnan(tim11)]=np.nanmin(tim11)  #fudge applied to 2017-309 to sort issues with
    ↪  calibration. Not used for day 2017-307!


    ##CONVERT IMAGES TO RADIANCE
    PT = 275                               #plume temp, PT, derived from opaque part of plume at
    ↪  10 microns. Failing that use an atmospheric profile and assume thermal equilibrium.
    rimg86 = c1*wav[0]**3/(np.exp(c2*wav[0]/tim86)-1.)      #converts T image (8.6 filter) to
    ↪  radiance image using Planck's function. Both 'tim86' and 'rimg86' are 200x200 arrays
    ↪  of summit cropped from 644x512 images
    #rimg10 = c1*wav[1]**3/(np.exp(c2*wav[1]/tim10)-1.)      #converts T image (10.0 filter)
    ↪  to radiance image using Planck's function.
    rimg11 = c1*wav[2]**3/(np.exp(c2*wav[2]/tim11)-1.)      #converts T image (11 filter) to
    ↪  radiance image using Planck's function.
    Tpr86 =  c1*wav[0]**3/(np.exp(c2*wav[0]/PT)-1.)         #UNKNOWN!
    Tpr11 =  c1*wav[0]**3/(np.exp(c2*wav[0]/PT)-1.)         #UNKNOWN!

    T_diff = tim11 - tim86


    """
    CORRECT IMAGES FOR ATM VARIATION IN TEMPERATURE - specific to instrument and acquisition
↪   day#
    USER NEEDS TO CHANGE THESE!!!!
    """
    ##IMAGE CORRECTION
    #Correct images for the atmospheric variation in temperature
    ylim = 140 #300-190 #ylim=300-235           #range of y pixels to go down to. (ie from top
    ↪  of image to this pixel number) at the pclear (see below) position. stop before you hit
    ↪  land, trees etc.

    n_rows = int(np.shape(tim86)[0])            #n_rows is integer value of length of first
    ↪  row of array 'tim86' (query shape of 'tim86' array in terminal with 'np.shape(tim86)')
    n_cols = int(np.shape(tim86)[1])            #n_cols is integer value of length of first
    ↪  row of array 'tim86'
```

```
                                                #NOTE THAT 'tim86' is a 512x644 image taken by NicAIR on 8.6 filter, so n_rows and n_cols are height and length, respectively, of each image in loop. Will be same for each image, hopefully (200x200 if cropped, 644x512 if not).

    kk = 4.3235E-5                              #kk is integrated absorbtion coeff (see Prata & Bernardo, 2014).  units are (umol/mol)^-1 m^-1


    T1 = np.copy(tim86)                         #creates a duplicate array of tim86
    #T2 = np.copy(tim10)                        #creates a duplicate array of tim10
    T3 = np.copy(tim11)                         #creates a duplicate array of tim11
    pclear = range(10, 25)                      #range of column positions (in x direction) that have clear sky in them. Avoid clouds and plume. Control values (360-264, 377-264) gives a 17x1 set of columns?
    L1 = ylim
    L0 = 0
    Tp = PT
    nrows = np.shape(T1)[0]

    ##POLYFITTING
    #Premise: take vertical slices through the two images, from the start line to the top of the image and poly fit to a linear sequence.
    #Polyfitting returns the coefficients for a polynomial p(x) of degree n that is the best fit for the data in y.
    zzi = np.zeros(L1)                          #make 'zzi', a 1D array of zeros with length L1 (ylim)
    #zzj = np.zeros(L1)                         #make 'zzj', a 1D array of zeros with length L1 (ylim)
    zzq = np.zeros(L1)                          #make 'zzq', a 1D array of zeros with length L1 (ylim)
    T1zz = np.zeros(nrows)                      #make a 1D array of zeros with length nrows () (this will be filled in later!)
    #T2zz = np.zeros(nrows)                     #make a 1D array of zeros with length nrows () (this will be filled in later!)
    T3zz = np.zeros(nrows)                      #make a 1D array of zeros with length nrows () (this will be filled in later!)

    for ww in range(0, L1):                     #for each value in range of ypixels (0 - largest value of y-pixel gone down to),
        zzi[ww] = np.nanmin(T1[ww,pclear])      #fills array 'zzi' with minimum non-NaN value of T1 array for length L1
        #zzj[ww] = np.nanmin(T2[ww,pclear])     #fills array 'zzj' with minimum non-NaN value of T2 array for length L1
        zzq[ww] = np.nanmin(T3[ww,pclear])      #fills array 'zzq' with minimum non-NaN value of T3 array for length L1
```

```

    for yy in range(0, nrows):
        T1zz[yy] = np.nanmin(T1[yy,pclear])     #fills array 'T1zz' with minimum non-NaN value
         ↪  of T1 array for length nrows
        #T2zz[yy] = np.nanmin(T2[yy,pclear])    #fills array 'T2zz' with minimum non-NaN value
         ↪  of T2 array for length nrows
        T3zz[yy] = np.nanmin(T3[yy,pclear])     #fills array 'T3zz' with minimum non-NaN value
         ↪  of T3 array for length nrows


    ##REPLACE NAN VALUES
    #Replace any NaN values in 'zzq' with mean value (excluding NaN) from associated line
    zzq[np.isnan(zzq)] = np.nanmean(zzq)        #N.B. this line was not used for images from
     ↪  Day 2017-307! (solution from notebook and 'so2maker_ailsa-bash_triple-plot_2.py')

    #zzi = array.array('d', (T1[i,pclear] for i in range (int(L0), int(L1))))
    #zzj = array.array('d', (T2[i,pclear] for i in range (int(L0), int(L1))))
    #zzq = array.array('d', (T3[i,pclear] for i in range (int(L0), int(L1))))
    yy  = array.array('i', (i for i in range (int(L0), int(L1))))          #creates an array
     ↪  of arrays (?) from first to last value in array
    yyz  = array.array('i', (i for i in range (int(0), int(n_rows))))

    #perform the polyfit
    resi = np.polyfit(yy, zzi, 2)
    #resj = np.polyfit(yy, zzj, 2)
    resq = np.polyfit(yy, zzq, 2)

    #use the coefficients
    b = np.multiply(yyz,yyz)
    toi = resi[2] + np.multiply(yyz,resi[1]) + np.multiply(b,resi[0])         #I THINK this
     ↪  gives radiance of image at wavelength of T1 (Lopez et al., 2014)
    toq = resq[2] + np.multiply(yyz,resq[1]) + np.multiply(b,resq[0])         #I THINK this
     ↪  gives radiance of image at wavelength of T3

    DTPi = [0]*T1
    #DTPj = [0]*T2
    DTPq = [0]*T3

    for k in range (0,n_rows):
        DTPi[k,:] = T1zz[k]  + Tp - toi[k]
        #DTPj[k,:] = T2zz[k]  + Tp - toj[k]
        DTPq[k,:] = T3zz[k]  + Tp - toq[k]

    DelTPi = T1
    #DelTPj = T2
    DelTPq = T3

    for m in range(0, n_cols):
```

```
        DelTPi[:,m] = T1[:, m] - toi[:]
        #DelTPj[:,m] = T2[:, m] - toj[:]
        DelTPq[:,m] = T3[:, m] - toq[:]

    #DTPij = DelTPi - DelTPj
    DTPiq = DelTPi - DelTPq                                             #I THINK this determines plume emissivity (see section 3.2.2 in Lopez et al., 2014)


    DZ = 1.0
    DY = 0.0


    #em = (DTPij-DTPi*DY)/(DTPj*DZ)
    em = (DTPiq-DTPi*DY)/(DTPq*DZ)

    em = median_filter(em, (3,3))

    #zem = em
    #zem = -np.log(1. - em[:,:])/kk                                       #optical depth of plume (from Lopez et al., 2014)
    zem = np.log(1. - em[:,:])/kk                                        #optical depth of plume? (from Lopez et al., 2014). Note this is the same as above, except positive. Don't know why it works better, but it seems to? See notebook pg. 51.


    """
    DO YOU NEED TO CROP TO SUMMIT?
    """
    ##SUMMIT CROPPING
    #crop to the region of the summit in this case
    #zem=zem[400:500,400:500]
    #rimg=rimg[200:400, 200:400]

    ##PLOTTING
    fig,(ax1) = plt.subplots(figsize=(6,6), ncols=1)                   #make a 6x6 figure with single column
    ima = ax1.imshow(zem, vmin=0, vmax=2000, cmap=cmap)                #vmax can be changed to max scaling value.
    imm = ax1.imshow(msk, cmap='gray')                                 #this plotting is very rudimentary and can be made a lot nicer!
    #imp=ax1.imshow(DTPi, alpha=0.5, cmap='viridis')                   #something to do with duplicate array of tim86. This might help you with your plotting problems ...
    #imp2=ax1.imshow(DTPij, cmap='inferno', a = 0.5)                   #further tests for plotting problems, to be tested and later deleted.
    #fig.colorbar(ima, ax=ax1)                                         #should be labelled. Units are ppm*m.
    #plt.colorbar(ima, fraction=0.046, pad=0.04, ax=ax1)
```

```
cbar_legend = plt.colorbar(ima, fraction=0.036, pad=0.04, ax=ax1)  #change fraction value
 ↪  manually to fit image height, change pad value to fit tightness of fit
cbar_legend.set_label('ppm/m', rotation = 90)                       #set colourbar title
ax1.set_title('SO2 image ' + str(int(fbase)))                       #set image title

#Annotations
#line1h = ax1.axhline(ylim, color='black', ls='--')
#ax1.annotate('ylim', xy=(45, 60))
#line1v = ax1.axvline(pclear[0], color='black', ls='--')
#ax1.annotate('pclear1', xy=(87, 25), rotation=90)
#line2v = ax1.axvline(pclear[-1], color='black', ls='--')
#ax1.annotate('pclear2', xy=(112, 25), rotation=90)

#Save outputs
fig.savefig(out_dir_so+str(int(fbase))+'_SO2.png', dpi=300)        #save each image in
 ↪  loop as png file with resolution 300dpi
plt.clf()                                                           #clear current figure
plt.close()                                                         #close plotting
 ↪  function
fbase2=str(fnamebase.split('/')[-1])                                #create new 1D-array
 ↪  (1xn) with filenamebase of so2 images


##WINDSPEEDS
#find the matching windspeed
for rows in numps:                                                  #iterate through each
 ↪  row in 'numps' aka array from windspeeds text file

    if rows[0] == fbase2:                                           #if you find entry in
     ↪  'numps' first row that matches name in 'fbase2' aka filenamebases of SO2 images:
        wspeed1 = float(rows[1])                                    #convert string value
         ↪  from corresponding second row into a floating point number and append it to
         ↪  1D-array 'wspeed1'
        wspeed2 = float(rows[2])                                    #convert string value
         ↪  from corresponding third row into a floating point number and append it to
         ↪  1D-array 'wspeed2'


wspeedmean = np.mean([wspeed1,wspeed2])                             #create 1D-array
 ↪  'wspeedmean' from mean of 'wspeed1' and 'wspeed2'

zem[zem <0] = 0.                                                    #something to do with
 ↪  the polyfit. Convert any negative values in array 'zem' to floating point values of
 ↪  0.0
np.nan_to_num(zem, copy = False)                                    #replace any NaN values
 ↪  in 'zem' with 0.0, copy = False replaces values in-place.

```

```
    linelength = 25                                                         #make this roughly
    ↪  similar or slightly more than the length of the line (is length of line given from
    ↪  'ylim'?)
    #xxx, yyy = np.linspace(xx[0], xx[1], linelength), np.linspace(yy[0], yy[1],linelength)
    xxx, yyy = np.linspace(56, 45, linelength), np.linspace(35, 55, linelength)  #coordinates
    ↪  of the ends of the transect line. Creates 'linlength' number of points along the
    ↪  co-ordinates specified for xxx and yyy

    good = np.where((yyy > 0) & (yyy < np.shape(zem)[0]) & (xxx > 0) & (xxx <
    ↪  np.shape(zem)[1]))       #evaluates quality of
    x2 = xxx[good]                                                          #UNKNOWN!
    y2 = yyy[good]                                                          #UNKNOWN!
    zi = zem[y2.astype(np.int), x2.astype(np.int)]                          #UNKWOWN!

    emmrate = np.sum(zi) * pix_h * wspeedmean*2.82E-3                       #emission rate derived
    ↪  from sum(quality test) x pixel height x windspeed x UNKNOWN!

    so2line = zem[32:52, 35]                                                #UNKNOWN!
    so2line[np.isnan(so2line)] = 0
    so2line[so2line < 0] = 0



    emmrate1 = np.sum(so2line) * pix_h * wspeedmean*2.82E-3                #emission rate
    time=datetime.datetime.strptime(idat, "%Y-%m-%d %H:%M:%S UTC").time()
    #print(emmrate, emmrate1)
    #print(wspeedmean)
    #print(time, emmrate1, tcal)

    ↪  the_file.write(str(time)+'\t'+str(emmrate)+'\t'+str(emmrate1)+'\t'+str(wspeedmean)+'\t'+str(round(t

    #optical depth at 10 micron calculation - allows for estimation of ash mass

    """
    #Optional: plot histogram of thermal images
    col_map = plt.get_cmap('coolwarm')                                     #choose your colourmap.
↪   Mine is blue/low to red/high.
    tim86_long = np.reshape(tim86, 40000)
    n, bins, patches = plt.hist(tim86_long, range=[200, 500], bins=100, color='green')
↪   #arguments are passed to np.histogram
    bin_centers = 0.5 * (bins[:-1] + bins[1:])
    # scale values to interval [0,1]
    col = bin_centers - min(bin_centers)
    col /= max(col)
    for c, p in zip(col, patches):
        plt.setp(p, 'facecolor', col_map(c))
    plt.title('Histogram of values for T_image ' + str(int(fbase)))
    plt.savefig(out_dir_hist+str(int(fbase))+'_T-image_histogram.png', dpi=300)
```

```
    plt.clf()
    plt.close()
    """

#the_file.close()


##FINAL STEP
#print time taken for script to execute
print('This script took {0} seconds to complete.'.format(t.time() - startTime))
```

CHAPTER 13

APPENDIX H: NICAIR CAMERA PARAMETERS

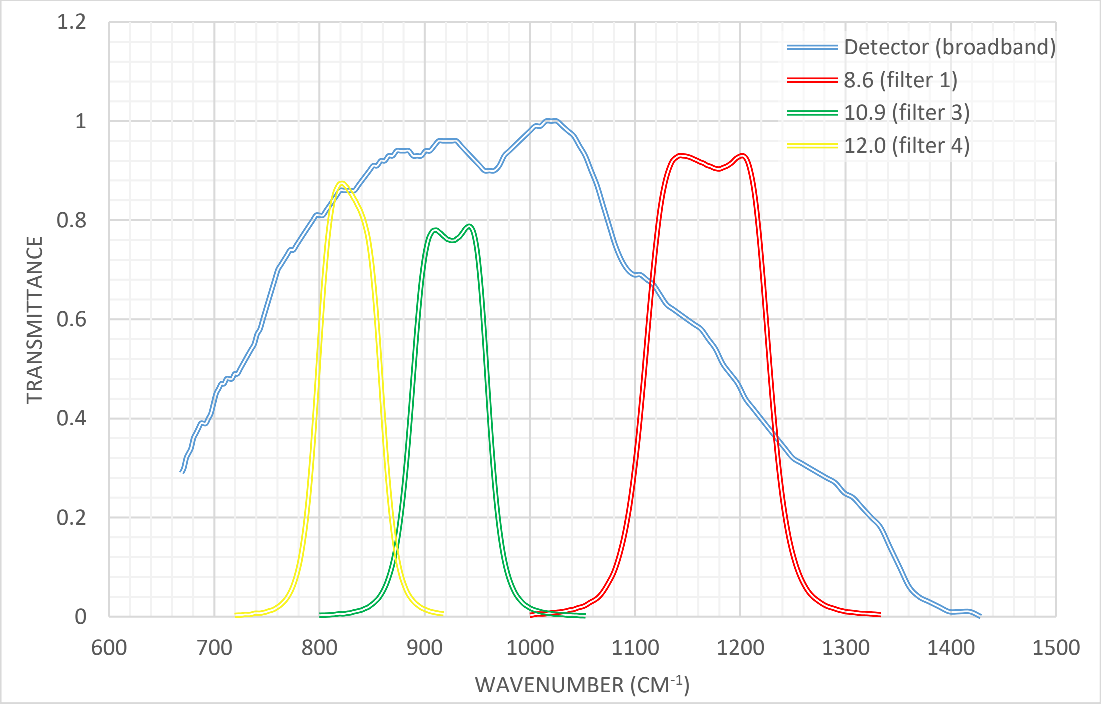
This appendix includes a PDF of parametric specifications, response functions, and calibration parameters for the NicAIR infrared camera used for monitoring changes in Volcán de Fuego's eruptive activity in Chapter 4.

NicAIR Infrared Volcano Monitoring Camera

Camera Specifics

Serial Number	NAIR 001/002/003/004
System Model	NicAIR I
Camera model	FLIR Systems Photon 640
Sampling Rate	9 Hz (max, single channel)
Focal Length *f number*	25 or 35 mm ¼
Field of view	26° (h) x 20° (v)
IFOV	0.714 mrad
Filters	4 out of a possible: 8.6 µm 10.0 10.87 µm 12.0 µm Broadband (no filter)
File type	.fits (not that files are written with .raw extension, which needs to be changed to .fits).

Camera Response Functions



Calibration Parameters

rimg= β *[chan]+ α *[chan]*DDNc+SHT*[chan]*rcal

Where β is the intercept of the slope, also know as the bias. A is the slope of the line and is also known as the gain. SHT is a coefficient that may be determined from the calibration procedure to account for the fact that the shutter is not a perfect blackbody. However, if only 2 coefficients are determined, SHT can be approximated as 1.0 .

Blue Camera:

Channel	Gain (α)	Bias (β)
1: 8.6	0.293	73.451
2: 10.0	0.345	100.76
3: 10.9	0.412	115.345
4: 12.0	0.593	130.57

Pink Camera (003):

Filter	Gain (α)	Bias (β)
1: 8.6	0.242	71.176
2: 10.0	0.241	97.82
3: 10.9	0.324	112.665
4: 12.0	0.441	127.527

Purple Camera (002)

Channel	Gain (α)	Bias (β)
1: 8.6	0.294	68.507
2: Broad	0.06	94.752
3: 10.9	0.464	109.187
4: 12.0	0.502	94.97

CHAPTER 14

APPENDIX J: NICAIR INSTRUMENTATION

This appendix is a detailed overview of the NicAIR camera system and set-up used for SO_2 monitoring at Fuego provided in Chapter 4. This appendix introduces NicAIR and describes its use in previous studies and its deployment and capture of eruptive activity at Fuego. This appendix also includes estimates of uncertainty for SO_2 capture using NicAIR.

14.0.1 Equipment: the NicAIR camera system

Thermal imaging cameras that use uncooled microbolometer array technology provide an attractive prospect for scientists who wish to measure volcanic emissions at high resolution, as such cameras are very sensitive to changes in temperature at salient wavelengths (50 mK at 8 – 12 μm) coupled with high-frequency image capture (up to 60 Hz) [Prata and Bernardo, 2009]. (In reality, co-adding of images to increase signal-to-noise ratio and filter-wheel rotation reduces this to ~0.5 Hz or lower.) Because commercial thermal imaging cameras are usually sold with a single broadband filter across the IR spectrum, the NicAIR camera system is installed with a multi-narrow band filter wheel to measure both volcanic ash and SO_2. Prata and Bernardo [2009] provide a summary of a camera they baptized "Cyclops", which was a prototype/predecessor for the NicAir instrument. Cyclops set-up appears in Figure 14.2. NicAIR detects SO_2 in the thermal infrared (TIR) range (7 – 14 μm) by exploiting features of the SO_2 absorption spectrum at 6.8 – 10 μm. The strongest absorption band within this range (C1 in Figure 14.1, transmittance 0.75 at 7.3 μm) is unsuitable for SO_2 detection from ground-based sites, given the strong absorption of water vapour masking any other signal. A second absorption peak at 8.6 μ m provides the solution as there is weaker influence of interfering absorption species (Figure 14.1). Cyclops's filter wheel can host up to four filters (indicated as C2 - C4 in Figure 14.1), which have bandwidths of ~1 μm each. The SO_2 channel on the filter wheel is thus centred around the absorption peak of 8.6 μm, with filter bandwidth of 8.2 – 9.2 μm giving a noise-equivalent temperature difference (NEδT) of 400 mK [Prata and Bernardo, 2014]. Retrievals of volcanic ash particle size, mass and optical depth from NicAIR are presented in Prata & Bernardo (2009), while retrieval of SO_2 from a multi-filter ground-based TIR camera are presented in Prata and Bernardo [2014]. Despite NicAIR's capacity to retrieve ash as well as SO_2, only SO_2 retrieval was undertaken to give results in Chapter 4. Figure 14.2 gives a simple set-up of the Cyclops prototype camera. The set-up of NicAIR differs slightly, as NicAIR's filter wheel which holds the bandpass filters is located in front of the lens.

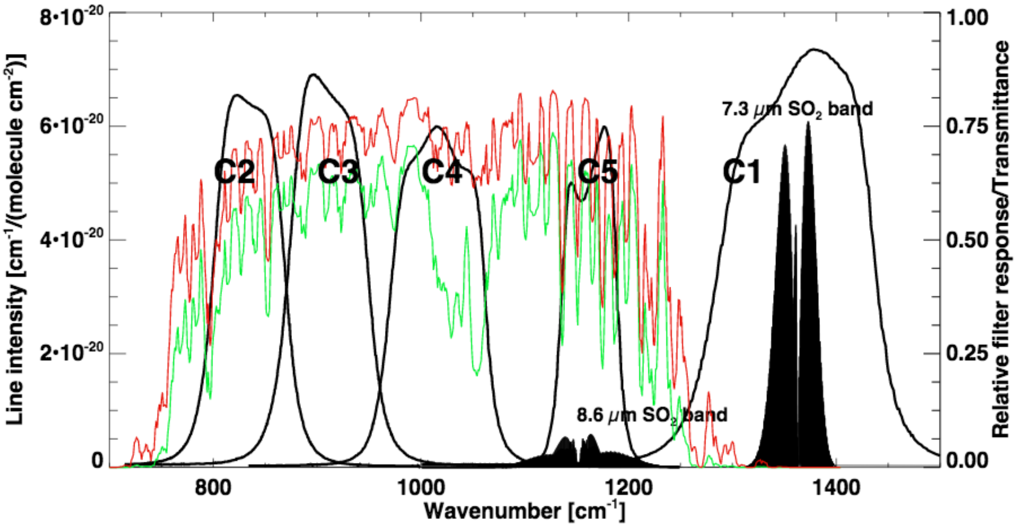


FIGURE 14.1. HITRAN (High Resolution Transmission) spectrum showing absorption features of SO_2 in TIR range. Shown are the two main SO_2 absorption bands at 7.3 μm and 8.6 μm, together with filter functions C1 - C5 (NicAir uses C2 - C5). Red and green lines indicate slant-path transmittances between the camera and target at ranges of 38 km and 6 km, respectively. From (Rothman (2003) via Prata & Bernardo (2014)).

Proof-of-concept of SO_2 and ash retrieval by NicAIR has been demonstrated at volcanoes whose behaviour is analogous to Fuego (e.g., Stromboli) [Lopez et al., 2015]. Early demonstrations of NicAIR's capabilities acknowledge that a single camera captures images on a 2D plane and is therefore unable to discern direction of plume travel. Although plume speed and direction can be traced by plume tracking, this was not easily compatible with NicAIR's operating frequency; therefore initial tests were completed in locations where SO_2 could be simultaneously measured by other means [Prata and Bernardo, 2009]. However, recent use of NicAIR with optical flow algorithms has allowed for advanced SO_2 retrieval for volcanic plumes and anthropogenic emissions [Thomas and Prata, 2018]. Multiple NicAIR cameras have lately been operated simultaneously to provide measurements of 3D volcanic plume properties [Wood et al., 2019].

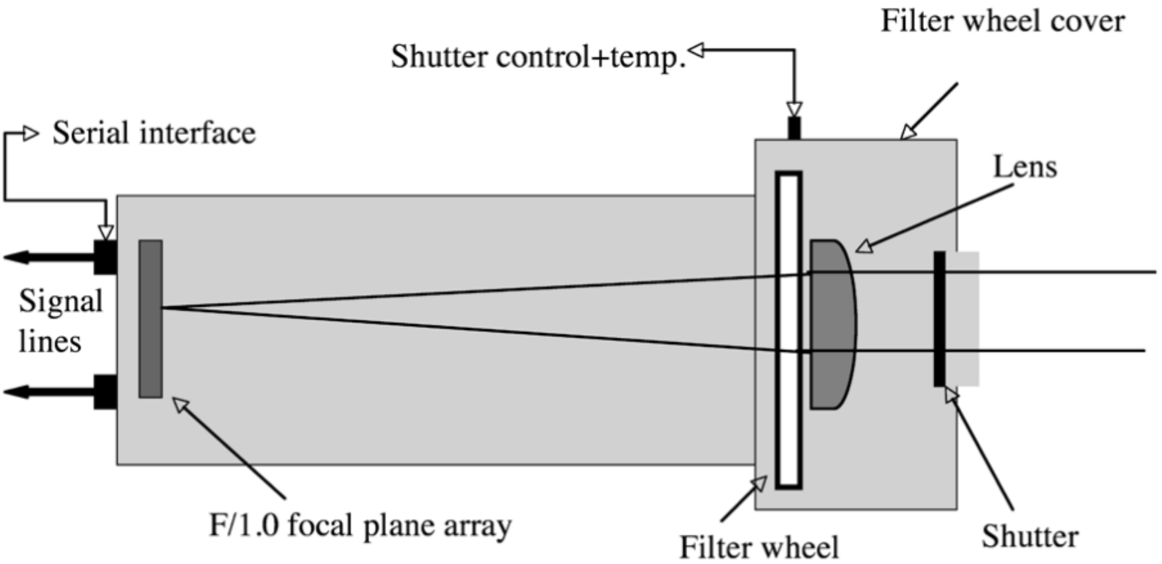


FIGURE 14.2. Schematic showing the main components of the "Cyclops" TIR imaging camera. Cyclops was the prototype camera from which the NicAIR camera was derived. There are minor differences between the two systems. For instance, NicAIR's filter wheel is located in front of the lens. From Prata & Bernardo (2014).

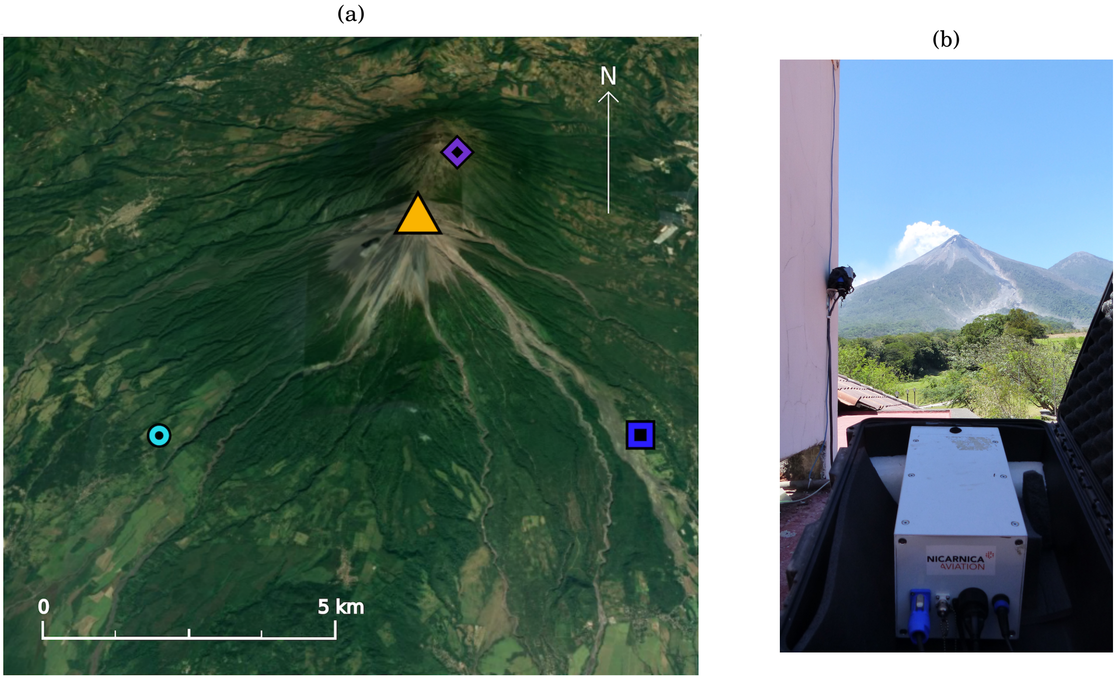
14.0.2 Deployment: location and coverage

NicAIR was first deployed at Fuego in January 2016 and remained operational until March 2020. The camera's location has changed in this period due to variable vulnerability to volcanic hazard and shifting research priorities. Figure 14.3 and Table 14.1 show NicAIR's location Jan 2016 – Mar 2020, and coverage in each location.

Location	**First deployment**	**End deployment**	**Operational coverage (HH:MM)**
OVFGO1	25/01/2016	02/03/2016	16:03
La Reunión	10/03/2016	11/07/2017	38108:57
OVFGO1	31/10/2017	present	385:46
Volcán Acatenango	03/11/2017	05/11/2017	07:12

Table 14.1: NicAIR coverage locations and coverage Jan 2016 – Mar 2020. Total 106 days coverage.

NicAIR's coverage of Fuego's activity is incomplete. This was mostly associated with remote


(a)

(b)

FIGURE 14.3. (a) Map of deployment locations of NicAIR camera around Fuego, Mar 2016 – Mar 2020. Turquoise circle represents INSIVUMEH's observatory, OVFGO1 in Panimaché Uno. Blue square represents La Reunión golf resort. Purple diamond represents terraces of Volcán Acatenango. Yellow triangle represents summit of Fuego. Deployment times: OVFGO1 (Mar 2016, Oct 2017 – Mar 2020); La Reunión (Mar 2016 – Jul 2017); Acatenango (Nov 2017). (b) Set-up of NicAIR at La Reunión (7.2 km from Fuego's summit). Table 14.1 gives total deployment times.

operation of the camera. The La Reunión golf resort was chosen as a deployment location for its apparently reliable power source and internet, allowing for easy remote operation from Bristol through TeamViewer software. In reality, internet and power at La Reunión were frequently interrupted by network failures due to thunderstorms. As the Cyclops software that runs NicAIR requires manual restart after loss of power, resumption of capture was dependent on collaboration with La Reunión staff. However, this collaboration was frequently not possible. Thus the system would typically remain offline until the next visit by INSIVUMEH or University of Bristol, resulting in the coverage gaps seen in Figure 14.4.

Despite these drawbacks, NicAIR has collected 106 days of data (38,510 hours) between February 2016 and June 2018 (Table 14.1). Of the 43 paroxysms in Jan 2015 – Jun 2018 (for further information, see Section 4.6) NicAIR has captured eight (Table 14.2). NicAIR has full coverage of four eruptions in this period: those beginning 28th July 2016, 27th September 2016, 5th November 2017, and 3rd June 2018. The eruptions are highlighted in Figure 14.4. Their evolutions are studied in detail in Chapter 4.6.

Year	Start date	No. (of regime)	No. of hours of capture
2016	01/03/2016	16	16:03:29
	28/07/2016	**21**	226:32:08
	27/09/2016	**23**	101:36:20
2017	26/01/2017	27	193:37:30
	25/02/2017	28	142:18:08
	01/04/2017	29	10:47:51
	11/07/2017	31	07:35:52
2018	**03/06/2018**	**39**	71:05:59

Table 14.2: All paroxysms Jan 2015 – Jun 2018 captured by NicAIR, with paroxysmal position in current eruptive regime (as presented in 2; Jan 2015 is No. 1) and number of hours of capture. Paroxysms captured in full are in **bold** text. Note that some paroxysms not captured in full have the largest number of hours of coverage; the apparent discrepancy is shown by Figure 14.4, which shows that these paroxysms have less cloud-free coverage.

Despite extensive coverage, many NicAIR data were not suitable for analysis due to cloud cover. Guatemala's rainy season occurs between April and October, and Fuego's summit is frequently obscured by cloud. NicAIR data were filtered to distinguish cloud-free imagery suitable for study. Filtering out cloudy images was achieved with the OpenCV image processing package in Python to process images on a day-by-day basis. For each day a subset of images (5 – 10) was chosen which included both cloudy and clear-sky images. This subset was read into Python and each image sequentially opened and a series of vertical transects drawn. For each transect, individual pixel values were plotted on an X-Y scatter plot. Average pixel values for transects drawn on clear-sky images were markedly lower than those for transects drawn on cloudy images. Lower averages from clear-sky transects are caused by low-value pixels representing low temperatures of the sky behind Fuego. A series of Boolean statements distinguished between cloudy and clear-sky images[1]. The script completed by processing all images in a directory (or day) and returning an integer value of the sum of all images categorized as "clear". The script proved to be an effective method for distinguishing between cloudy and clear-sky images, and could easily be quality-checked by evaluation of the image subset by eye. The full cloud-filtering script can be found in Appendix F (Chapter 11).

14.0.3 SO_2 processing

Once cloud-free imagery was distinguished, data were processed to produce SO_2 images using Python. The processing script is in Appendix G (Chapter 12). Images were separated by day into a directory. For each directory, FITS input images were loaded sequentially by the script. Although

---

[1] For example: *If (40 ≤ np.average(pixels_2) ≤ 160): print "Image is clear"; else: print "Image is cloudy"*, where np.average(pixels_2) gives the average of all pixel values across the transect called pixels_2.

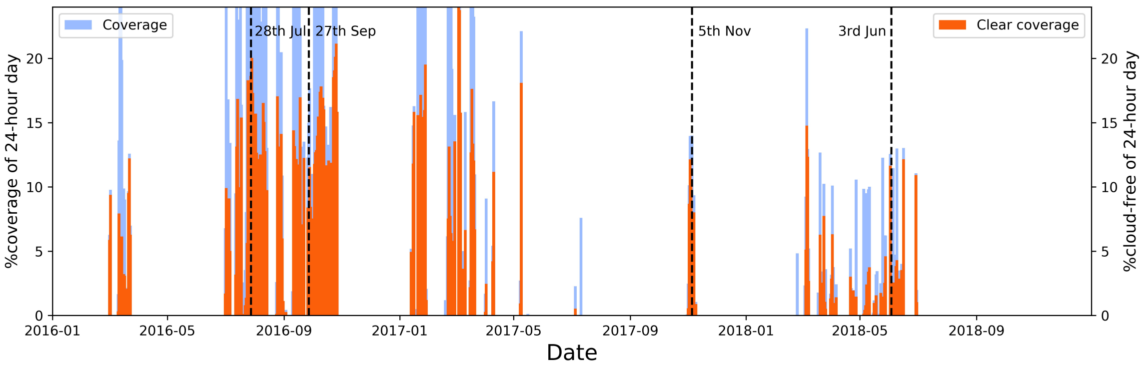


FIGURE 14.4. NicAIR coverage between March 2016 and June 2018 (light blue) and cloud-free coverage (orange). Individual eruptive event illustrated by dashed vertical lines; date refers to beginning date of paroxysm, according to INSIVUMEH bulletins. Eruption of 5^{th} November 2017 is classed by INSIVUMEH as an effusive eruption instead of a paroxysmal eruption.

in FITS format, images had a .raw extension, so each image was renamed with a .fits extension before being cropped to 200x200 pixels. A mask was applied to Fuego's summit. Individual camera parameters had to specified: camera distance from volcano (km), the angle camera was pointing above horizontal (degrees), the camera half-field-of-view (FoV) (degrees), and the number of pixels both in x and y direction. Image files were sorted and matched to the closest calibration file in the directory. Calibration coefficients were specified (Table 14.3) depending on the date of operation, location, and camera model used. Four models of NicAIR camera were used to capture SO_2 data presented in Chapter 4, each with different calibration coefficients including the wavenumber of filters in the filter wheel, gain, and offset. Information on NicAIR camera specifics, response functions, and calibration parameters appear in Appendix H (Chapter 13). Table 14.3 gives calibration coefficients for Lazarus, which was the model used for ~95% of the data presented in Chapter 4. Calibration of NicAIR is a two-step process, involving both laboratory and field calibrations. This is necessary to estimate the gain α and intercept β required to convert digital numbers (DN) captured by NicAIR into radiances and subsequently to brightness temperatures. Calibration is first performed under controlled conditions in the laboratory, using a blackbody source. Estimates for α and β on the DN-radiance calibration line are obtained for multiple source and environmental conditions. However, environmental conditions in the field will be considerably more variable than those simulated in the laboratory. Therefore, an additional step is taken to mitigate some of the largest environmental variables, associated with temperature of the instrument and housing. In this second step, a blackbody shutter built into the NicAIR housing is periodically placed in front of the camera so that a calibration point is captured between points of data capture. As the periodicity of shutter placement is computer controlled, this in-field calibration can be performed as frequently as desired. Additional explanation of the two-step calibration process appears in Prata and Bernardo [2009]. However, the explanation above should be sufficient to understand the origin of calibration coefficients given in Table 14.3. The coefficient LM is a correction for the fact that the camera shutter is not a perfect blackbody: LM is the mean ratio between the predicted temperature for a perfect blackbody (determined by the Planck function below) and the measured temperature for the shutter blackbody (determined by both laboratory and in-field calibrations of the NicAIR instrument). As detailed above, the gain α and slope β of the DN-radiance calibration line needed to obtain brightness temperatures are estimated through laboratory calibration and validated by subsequent in-field calibration.

Calibration coefficient	**Meaning**	**Channels (centred on μm)**	**Values (corresponds to channel)**
Wavenumber	Wavenumber of filters in filter wheel	8.65, 10.0, 10.87, 12.0	10000./8.65, 10000./10.00, 10000./10.87, 10000./12.0
Beta (β)	Bias (intercept of calibration line)	"	-0.745, 27.14, 41.912, 26.659
Alpha (α)	Gain (slope of calibration line)	"	0.31, 0.295, 0.384, 0.054
LM	Difference between shutter and perfect blackbody	"	1.000, 0.735, 0.644, 0.735
Image offsets	Values for shutter calibration	"	0., 0., -5, 0

Table 14.3: Calibration coefficients for NicAIR camera, specific to day and camera model. The above values are for the "Purple" camera operating at OVFGO1 on 03/11/2017. Additional explanations of calibration coefficients can be found in Appendix H (Chapter 13).

Radiance is converted to brightness temperature using a variant of Planck's law. As the law can be expressed in terms of multiple spectral variables, wavelength is the variable pertinent to this chapter. The law is then expressed as:

$$L(\lambda, t) = \frac{c_1}{\lambda^5(e^{c_2/\lambda t} - 1)}$$

Where $L(\lambda, t)$ is blackbody radiance in W/m^2-sr-μm, c_1 is the constant 1.191042 x 10^8 (W/m^2-sr-μm^{-4}), c_2 is the constant 1.4387752 x 10^4 K μ m, λ is wavelength (μm), and t is blackbody temperature (K). c_1 and c_2 are known respectively as the first and second radiation constants. In this variant of Planck's law, they can be expressed as physical constants with:

$$c_1 = 2hc^2$$

and

$$c_2 = hc/k_B$$

Where h is the Planck constant ($6.62607015 \times 10^{-34}$ J), c is the speed of light (2.99792458×10^{8} m s^{-1}), and k_B is the Boltzmann constant (1.380649×10^{-23} J K^{-1}). The equation for the wavelength variant of Planck's law can be found here (`https://ncc.nesdis.noaa.gov/data/planck.html`) and its use with NicAIR is explored in Albina et al. [2014]. For more information on the SO_2 retrieval, see either Appendix B of Lopez et al. [2013a] or Prata and Bernardo [2014].

14.0.4 Errors and uncertainties

Lopez (2012) estimates total uncertainty of ±50% in NicAIR's SO_2 measurements. Specific conditions required for optimal operation of the NicAIR camera are clear sky, low to moderate winds, and a translucent plume. The absolute error in SO_2 column density and derived emission rates associated with NicAIR are poorly constrained and a full work-up is yet to be done [Lopez et al., 2013b]. Validation of SO_2 capture with NicAIR has resulted in slant column density (SCD) errors of 20% [Prata and Bernardo, 2014]. In previous field campaigns, an estimated half of signal variability is due to poor calibration, retrieval error, and errors in estimating plume temperature and wind speed [Lopez et al., 2015]. Despite the relatively high uncertainties involved in data collection and processing, NicAIR gives cromulent results of SO_2 fluxes at high temporal resolution. A significant advantage NicAIR has over other SO_2 cameras is that it does not require an independent plume speed estimate, which may introduce an additional error to derived values of up to 40% [Lopez et al., 2013b].

Prata and Bernardo [2014] cite three main sources of error associated with NicAIR data capture. These are (1) errors associated with noise; (2) errors associated with assumptions in retrieval; (3) errors associated with inadequate parameter specification. The first source of error can be attributed to noise-equivalent temperature differences (NEδT) producing a signal-to-noise ratio (SNR) for any pixel in the camera. These can be qualified by comparison of field and laboratory calibrations of NicAIR, that give a temperature error of <0.1 K, corresponding to a calibration accuracy of ± 0.5 K. This calibration accuracy translates to an error in SO_2 SCD of ± 5% [Prata and Bernardo, 2014]. Lopez et al. [2014] give a higher estimate of SO_2 SCD error of ~20%, although noted that full error assessments for gas and ash retrieval for the NicAIR camera have not yet been made. Lopez et al. [2015] cite errors in wind speed estimates as a considerable source of uncertainty for SO_2 retrieval with NicAIR. This is likely true for SO_2 retrievals in this thesis, given that estimates were simple values obtained from nearby weather stations and the strong and variable winds at Fuego's summit. However, quantification of this uncertainty is not possible.

Error type	**Error source**	**Uncertainty in *m (%)**
I	NEδT	±9 - 10
I	Absolute calibration	±5
II	RT model	±2
II	Linearization	±5
II	Plume temperature	±12-14
II	Absorption coefficient spatial variability	(< 1?)
II	Transmission approximation	+3
II	Atmospheric invariance	±3
III	Absorption coefficient	< 1
III	Geometry	< 0.5
III	Radiosonde	-

Table 14.4: Sources of error and respective magnitudes for SO_2 retrieval with NicAIR camera. From Prata & Bernardo (2014).

The second group of errors include factors such as a constant plume temperature and invariance of the atmospheric structure [Prata and Bernardo, 2014]. Similarly, errors associated with poor parameterisation (Group 3) include factors such as errors in specifying camera geometry and channel filter response functions. These are explored in detail in Prata and Bernardo [2014], who found a total error on SO_2 retrieval for the NicAIR camera to be ~ 20% with a bias of -5 to +6%. Table 14.4 summarizes error types and magnitudes for each of the three groups of errors considered in Prata and Bernardo [2014].

CHAPTER 15

APPENDIX K: SPECTROSCOPIC REMOTE SENSING LITERATURE REVIEW

This appendix is a brief literature review of spectroscopic remote sensing techniques for the detection and measurement of volcanic gases. The appendix includes a brief history of studies at Fuego and describes previous studies using the NicAIR system that produced SO_2 data for eruption timeseries presented in Chapter 4.

15.0.0.1 SO_2 degassing at open-vent systems

Measurement of sulphur dioxide (SO_2) gas emissions has been a cornerstone of volcanic monitoring since the successful development of the correlation spectrometer (COSPEC) in the 1970s (e.g., Hoff and Gallant [1980]). SO_2 is a useful tracer for volcanic activity due to its high concentration in eruptive plumes. Because it is otherwise scarcely found in Earth's atmosphere, the gas can easily be identified as a product of eruptive activity [Kern et al., 2015].

In the four decades since the development of the COSPEC, advances in instrumentation have afforded volcanologists increasingly sophisticated methods of detecting SO_2 at active volcanoes. Interpreting patterns in SO_2 degassing is an elegant way to decode a range of eruptive behavioural changes. Instrumentation using the ultraviolet (UV) range of the electromagnetic spectrum to detect SO_2 forms the majority of recent academic studies. However, instruments that detect SO_2 by other methods, particularly within the infrared (IR) range, are gaining prominence.

The prevalence of UV as a spectral window for detecting SO_2 is due to the strong absorbance of SO_2 within that window, but also to the relatively simple retrievals and low sensor costs [Tamburello et al., 2011]. Instruments based on differential optical absorption spectroscopy (DOAS) are a primary method of capturing SO_2 emissions from volcanoes. A detailed history of using DOAS to capture volcanic SO_2 appears in Platt et al. (2008) [Platt and Stutz, 2008]. DOAS measurements have the ability to capture multiple volatile species in volcanic plumes including SO_2, CO_2, halogens [Platt and Perner, 1980], and most recently, water vapour [Kern et al., 2017]. The diversity of DOAS instruments affords a variety benefits: passive DOAS (i.e., using the sun as a light source) allows for easier quantification of volcanic fluxes, while active DOAS (which uses an artificial light source) is operable by night [Kern et al., 2009].

Recent advances in UV detection of SO_2 have allowed UV to further dominate field campaigns and literature on SO_2 detection. These advances include simultaneous detection of SO_2 with other volatile species, developments in scanning, and wide-angle DOAS that allows for much greater temporal resolution of SO_2 data capture in daylight hours [Tamburello et al., 2011]. Automatic DOAS networks have also been tested to good effect in Chile, which promises more extensive monitoring coverage of Latin American volcanoes in future [Galle et al., 2010]. Greater constraints on errors and high sampling rate (~1Hz) of gas and geophysical datasets have further enhanced the fidelity of UV imaging instruments [McGonigle et al., 2017]. Meanwhile, development of low-cost systems like the smartphone UV camera, "PiCam" [Wilkes et al., 2016], promises greater inclusion of UV cameras in volcanic monitoring networks worldwide.

Although UV cameras have previously led developments in SO_2 detection at active volcanoes, other methods show promise. Thermal emission spectroscopy has the distinct advantages over UV cameras of being able to detect other species such as ash [Prata and Bernardo, 2009], and of being operable at all hours (i.e., including at night). The latter is of particular use at tropical volcanoes like Fuego, where orographic cloud cover occurs during most daylight hours. Disadvantages of other infrared spectroscopic techniques (e.g., FTIR) include complicated set-up and necessary cryogenic cooling [Platt et al., 2018]. However, these are not pertinent to the camera used in Chapter 4. Platt et al. [2018] devote a short section in a review article to thermal infrared spectroscopy, and suggest this is a majorly under-researched subset of spectroscopic SO_2 detection. Figure 15.1 positions the NicAIR camera used in Chapter 4 within the family of techniques described by Platt et al. [2018].

The family tree of spectroscopic remote sensing has produced a cornucopia of knowledge of degassing dynamics at active volcanoes. This includes volcanoes of all magmatic compositions. Advances in UV remote sensing techniques have contributed to understanding of SO_2 degassing dynamics at silicic dome-forming volcanoes such as Soufrière Hills Volcano (Montserrat). COSPEC measurements that correlated with geophysical signals across a dome-building cycle indicated a rise in gas-rich magma and/or increase in flow rate [Watson et al., 2000]. An innovative automated UV scanning system traced SO_2 emissions that were shown to vary across multiple timescales as well as tie with volcanic activity [Edmonds et al., 2003]. A decade later, sophisticated analysis of the system determined multiple timescales of SO_2 cyclicity and proposed a common source process of enhanced marginal shear strain associated with repeated magma acceleration to

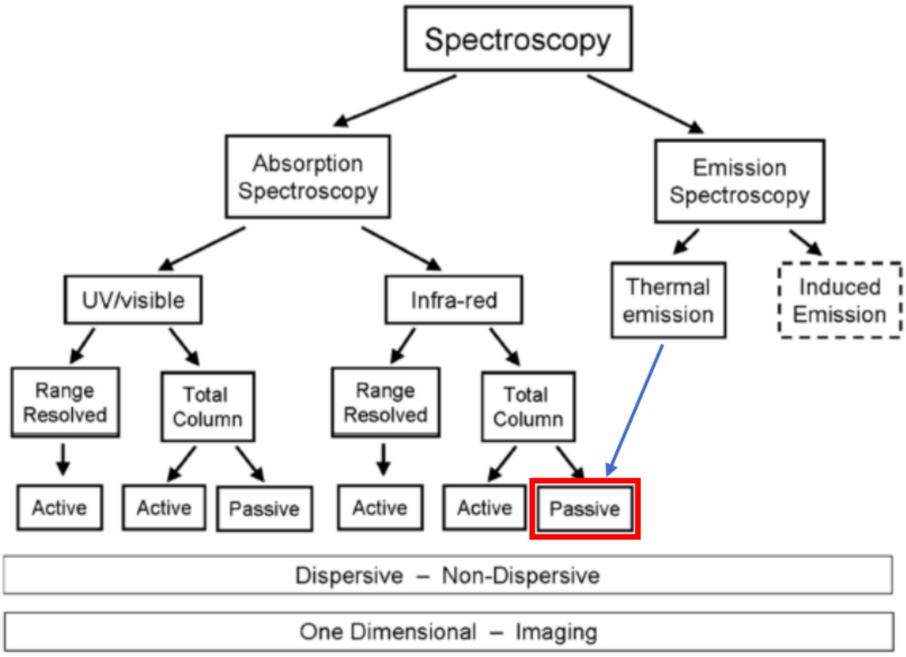


FIGURE 15.1. Family tree of spectroscopic remote sensing schemes annotated with character of the camera used in this chapter outlined in red. Light source is described as "active" (using artificial source) or "passive" (using sun or other natural radiation). Blue arrow shows instances of IR spectroscopy when instrument is below plume and measures emission rather than absorption. Adapted from Platt et al. (2018).

surface [Nicholson et al., 2013].

Spectroscopic remote sensing shows that transitions between effusive and explosive activity also occur at volcanoes of intermediate (andesitic-dacitic) composition. These volcanoes may erupt explosively (e.g., MSH in 1980 [Sparks et al., 1986]) but also produce extensive lava flows (e.g., MSH in 2008 [Anderson and Segall, 2013]). This variability (and its implications for hazard) motivates research into what controls this effusive-explosive transition. A seminal paper exploring the transition to open-system degassing at Volcán Santiaguito (Guatemala) found the volcano followed cycles of explosive activity interspersed with continuous passive degassing [Holland et al., 2011]. Analysis using a UV camera showed shear fracturing that facilitated open-system degassing during ascent of intermediate magma [Holland et al., 2011]. The paper traced a system which had a remarkably clear threshold for the explosive-effusive transition. Fortunately for the careers of volcanologists, most other volcanic systems are less predictable.

Although their nature allows frequent capture of gas data, open-vent mafic volcanoes are not easy to understand. They often show a large variety of eruptive styles. For example, seething magma, lava fountaining, and Strombolian explosions were all characterized by different SO_2 profiles at Volcán Villarrica (Chile) [Palma et al., 2008]. Uniting SO_2 flux and geophysical measurements can effectively trace open-vent eruptive styles and transitions between. Easily accessible and persistently active, Stromboli (Italy) is perhaps the most well-studied open-vent system. During a period of eruptive activity in 1999, Ripepe et al. [2002] deployed multiple sensors to detect discrete gas burst events. These events were interpreted to be the culmination of ascent, accumulation and coalescence of gas bubbles in the conduit. Associated very-long-period (VLP) seismicity has been determined to be the expansion of these bubbles as they rise and decompress in Stromboli's upper conduit [Ripepe et al., 2002]. Subsequently, Ripepe and colleagues united gas and geophysical monitoring to trace an effusive-to-explosive transition in December 2002 – July 2003 [Ripepe et al., 2005]. The transition between explosive and effusive activity was controlled by (1) a decrease in magma volume flux below a threshold value, and (2) a rise of magma level within the conduit [Ripepe et al., 2005]. Figure 15.2 shows the data sets of all geophysical and gas parameters measured in this study. The data sets are visualized as cumulative functions to easily visualize patterns in data. These cumulative functions were determined by calculating daily averages of each parameter then plotting results cumulatively. Change in gradient of line indicates a change in rate of that parameter (e.g., a decrease in gradient of SO_2 after the transitional period indicates a decrease in SO_2 flux after Stromboli's behaviour had moved from transitional to explosive. Figure 15.2 shows that daily averages of (1) VLP events per hour (dashed line), and (2) SO_2 flux (stippled line) are mirrored: both show a decrease in gradient after July 21, when lava effusion ceased. During effusion, 450 T/day of SO_2 and 18 VLP events per hour were recorded. After effusion ceased, SO_2 flux and VLP event rates decreased by half. This common trend suggests that gas flux is a strong control on bubble coalescence rates at Stromboli. To explain the effusive-explosive transition, the authors propose a gas-driven model in which Stromboli's conduit hosts an equilibrium between gas flux and gas overpressure. Changes in this equilibrium is the deciding factor of whether the system will support effusive or explosive activity. Other authors support a magma-driven model and have used SO_2 to propose that magma level in Stromboli's conduit is the primary control on transitions between eruptive style [Burton et al., 2009]. The latter model is supported by triangulation with long-term satellite remote sensing timeseries data [Coppola et al., 2012]. My own research supports a magma-driven model for eruptions of Fuego; I invoke a similar mechanism to Coppola et al. [2012] to propose that magma level in the upper conduit acts as a primary control on transitions in eruptive behaviour at Fuego [Naismith et al., 2019a].

Research continues to explore transitions between effusive and explosive activity of Stromboli using SO_2 flux data. This in turn fuels the continuing debate of gas-driven vs magma-driven explanations for the transition. A study by Delle Donne et al. [2017] has traced the transition between explosive and effusive activity at Stromboli between 2014 and 2016. This encompassed the effusive eruption of August – November 2014. Findings of SO_2 fluxes at double average level

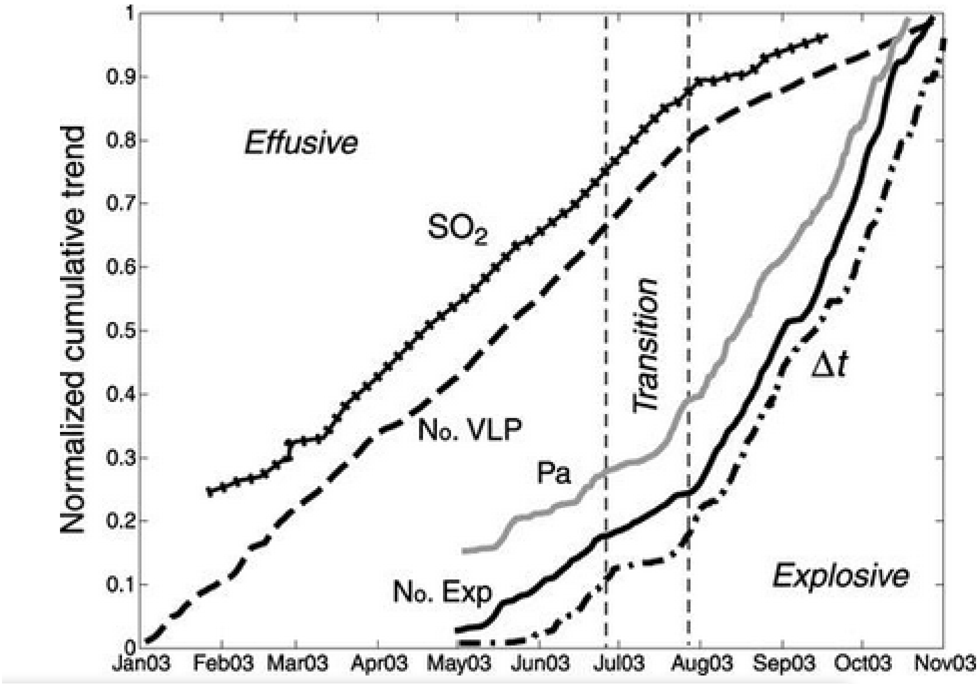


FIGURE 15.2. Transition from effusive to explosive eruptive activity at Stromboli in 2003. This figure shows cumulative values of daily averages for multiple parameters, including SO_2 flux and hourly VLP event rates, measured across ten months of activity in 2003. From Ripepe et al. (2005).

in the months preceding the effusive eruption was interpreted as elevated supply of gas bubbles to Stromboli's shallow conduits. The bubble supply, fuelled by an increased magma supply rate, encouraged explosive activity before effusive eruption was triggered by the rising magma that followed the bubbles [Delle Donne et al., 2017].

SO_2 traces eruptive transitions at many open-vent systems other than Stromboli (Figure 15.3). At Volcán Turrialba in Costa Rica, five years of SO_2 flux data revealed one year of steady gas emission before acceleration in degassing before a phreatic eruption in January 2010 [Conde et al., 2014]. As at Stromboli, SO_2 degassing at Turrialba reflects seismicity, although at Turrialba it is long-period (LP) seismicity rather than VLP. Continuous SO_2 measurements at Volcán Tungurahua between 2007 and 2013 distinguished between continuous and episodic behaviours [Battaglia et al., 2013]. The two behaviours identified were (1) sudden eruptive onset characterised by energetic Vulcanian explosions that unblocked the conduit, and (2) progressive development towards eruption. Interestingly, towards the end of the observation period Tungurahua had periods of quiescent behaviour, associated with plugging of the conduit and minimal SO_2 degassing. Quiescence was interrupted by unblocking the conduit with violent Vulcanian eruptions, which has important hazard implications [Battaglia et al., 2013]. At Etna, comparison of SO_2 degassing associated with paroxysm in 2014 – 2016 revealed interesting consistencies in pre-, syn-, and post-paroxysmal degassing trends [Delle Donne et al., 2019]. Figure 15.4 shows these trends, with a pronounced acceleration in SO_2 degassing during the syn-eruptive phase of paroxysm (illustrated by the shaded region).

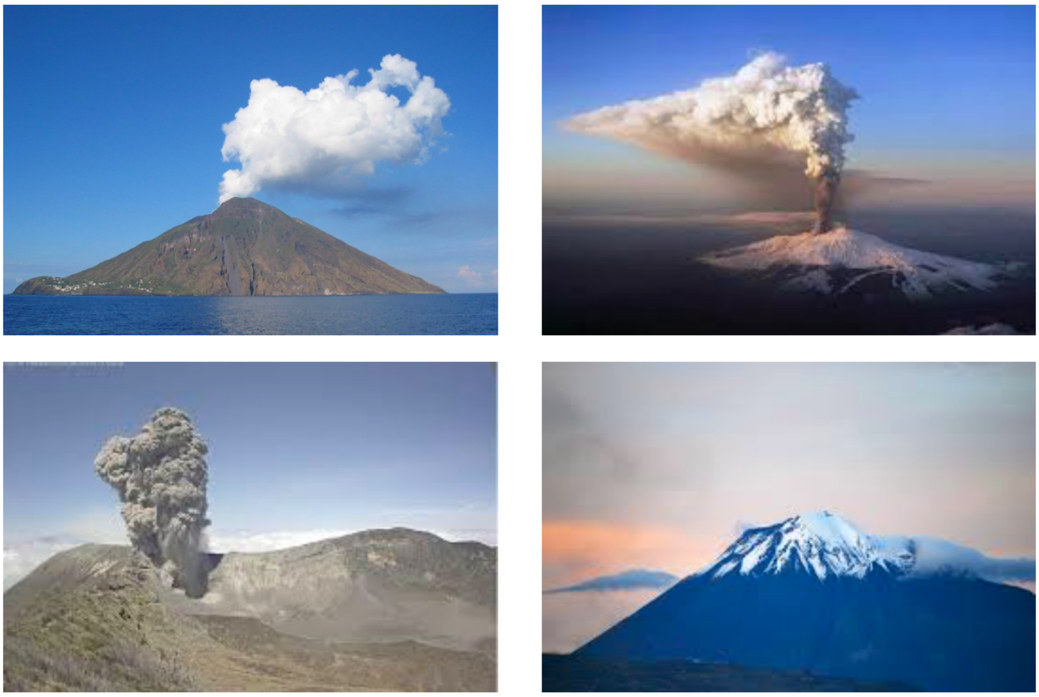


FIGURE 15.3. Analogue open-vent volcanoes whose transitional eruptive styles have been studied by tracing SO_2 degassing. Clockwise from top left: Stromboli (Italy), Etna (Italy), Tungurahua (Ecuador), Turrialba (Costa Rica). Images from first page of Wikipedia.

In fact, all of the above studies use UV cameras to reveal degassing insights into different volcanoes. IR cameras have also been used successfully to understand SO_2 patterns associated with volcanic activity at open-vent volcanoes. For example, measurements at 0.5 and 4 cm^{-1} using ground-based thermal emission infrared spectroscopy at Volcán Popocatépetl (Mexico) revealed SO_2 and SiF_4 emissions [Stremme et al., 2012]. More recently, camera systems using uncooled microbolometers to produce hyperspectral images of volcanic plumes have been tested and validated in the field [Gabrieli et al., 2016, 2017]. Lopez et al. [2015] traced patterns at three volcanoes (Stromboli, Volcán Lascar (Chile), Karymynsky (Russia)) using the same uncooled microbolometer IR camera system that gives results of this chapter. I identified Stromboli as a potential analogue to Fuego in Chapter 2. Because NicAIR has already used successfully to trace degassing patterns at analogue volcanoes, this endorses its use at Fuego and encourages hopeful results and direct comparison between the systems. Figure 15.5 shows NicAIR capturing SO_2 at Stromboli.

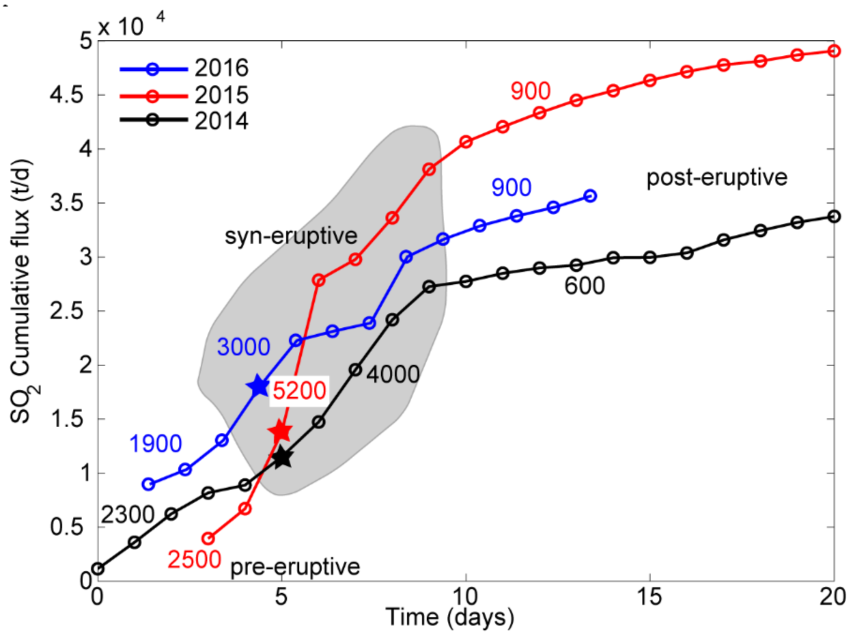


FIGURE 15.4. Comparison of cumulative SO_2 flux trends from three paroxysmal sequences at Mt. Etna in 2014 – 2016. Similar trends visible in pre-, syn-, and post-paroxysmal SO_2 degassing trends in lava fountaining associated with lava fountaining during paroxysm. Stars represent onset of paroxysmal eruption. Shaded region bounds the time in days that contains the paroxysmal episode of the three eruptions studied. From Delle Donne et al. (2019).

Despite the excellent work of Lopez et al. (2015), in the five years since its publication there have been relatively few studies of IR detection of SO_2 to study transitional (either effusive-explosive or explosive-effusive) behaviour at active volcanoes. This excepts a recent thesis on estimation of SO_2 in volcanic plumes of Chilean volcanoes [Sotomayor, 2019]. This shortfall points to a “gap in the market” which this chapter attempts to fill. One major advantage of IR spectroscopy is that it is operable overnight for hours of extra data. Such data can be combined with other parameters for effective multiparametric monitoring of transitional behaviour, as explored in detail in Chapter 4.3.1.

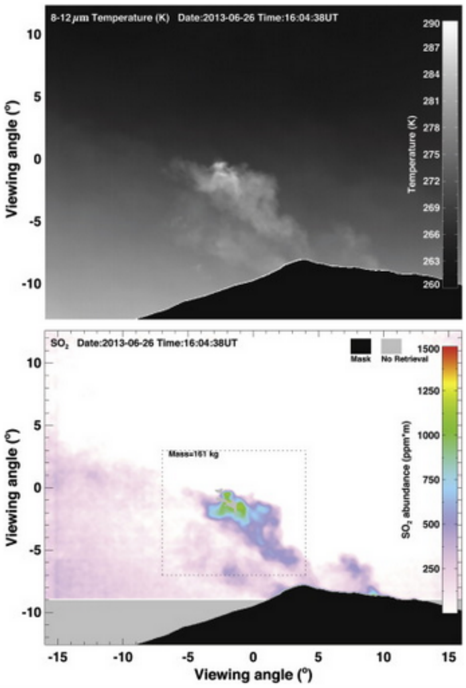


FIGURE 15.5. Capture of SO_2 at Stromboli volcano with NicAIR. From Lopez et al. (2015).

15.0.1 History of SO_2 studies at Fuego

Several authors have explored Fuego's degassing dynamics. Table 15.1 and Figure 15.6 summarize findings of previous studies. The results of each study are explored below.

Crafford [1975] determined an average emission rate of 423 T/day from Fuego between October and December 1974. Interestingly, SO_2 concentration within Fuego's plume appeared to increase as the plume waned. Andres et al. [1993] made the first attempt to link patterns in degassing with subsurface dynamics driving activity. They concluded that SO_2 fluxes were consistent with a high-level magma body crystallizing and releasing volatiles. The authors estimated Fuego's 20-year average SO_2 emission rate at 160 T/day [Andres et al., 1993]. This value is significantly lower than Crafford's. However, it is consistent with Fuego's two decades of near-total quiescence between 1979 and 1999. The larger average of 340 T/day measured between 1999 and 2002 [Rodríguez et al., 2004] is also reflective of changes in eruptive activity, as it marks Fuego's reactivation in 1999.

Nadeau et al. [2011] conducted perhaps the first multi-parametric analysis of short-term changes in Fuego's activity through simultaneous deployment of a UV camera and seismometers near Fuego's summit crater in 2009. Patterns in SO_2 emissions and seismic events were related to distinct explosive events that shared a common source process of magma stiffening in Fuego's upper conduit. Recent camera measurements of SO_2 flux at Fuego show that only ~5% is quiescent gas flux, while ~95% is associated with explosive activity [Waite et al., 2013, Burton et al., 2015].

Both Nadeau et al.'s study and the onset of a new eruptive regime in 2015 held promise for reinvigorated academic interest in Fuego's degassing dynamics. Unfortunately, in the last decade there have been relatively few studies focussing on SO_2 degassing at Fuego. This situation may change. Recent advancements in satellite data resolution and accessibility have allowed for detection of SO_2 degassing patterns at unprecedentedly high temporal resolution (e.g., Pardini et al. [2019]). These papers represent a step change in resolution of space-based detection of volcanic emissions and hopefully usher in a new interest in degassing dynamics of Fuego.

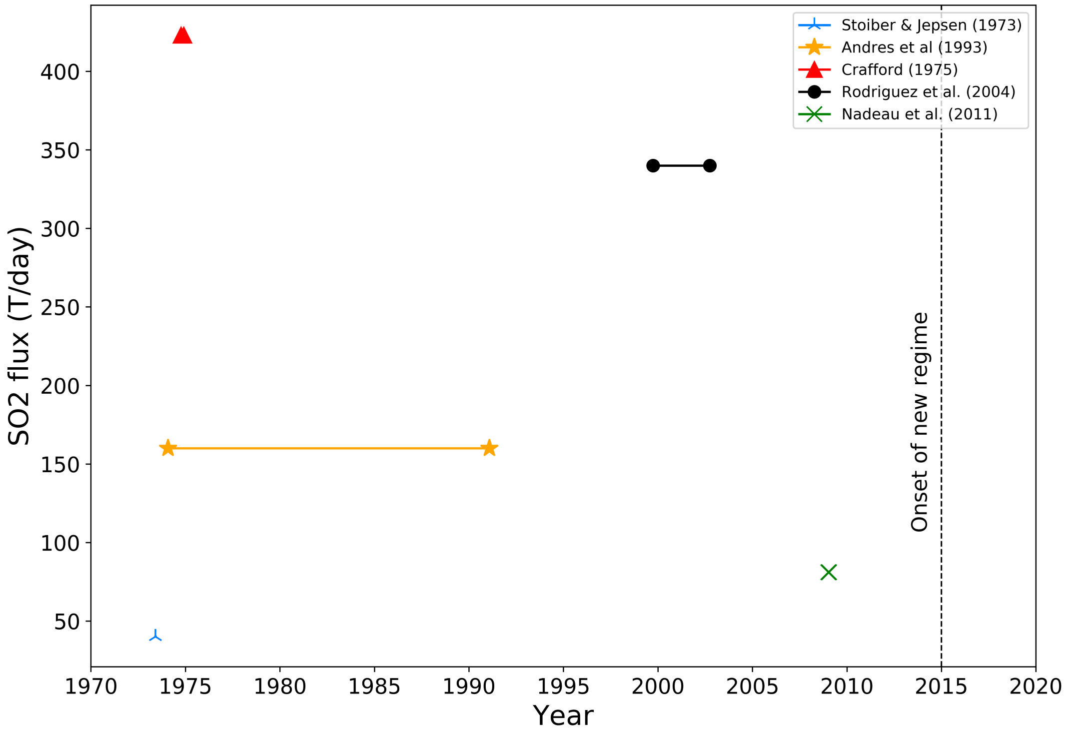


FIGURE 15.6. Illustration of Table 15.1 showing previous studies of degassing at Fuego and onset of new eruptive regime as described in Chapter 2. Most recent published data is from Nadeau et al. (2011).

Paper	**Key findings**	**Daily SO_2 flux averaged across study period (T/-day)**	**Length of study**
Stoiber & Jepsen (1973)	Average SO_2 of 40 T/day recorded	40 T/day (N/A)	
Crafford (1975)	Maximum flux of 1201 T/day recorded on 14th Nov 1974. Measurements show broad SO_2 peak during eruptive cluster followed by rapid decline. Eruption produced 25 kT SO_2 (this study) or 220 kT SO_2 (other sources)	423 T/day (Oct – Dec 1974)	37 days
Andres et al. (1993)	Maximum flux of 3300 T/day recorded on 24th Feb 1978. Daily flux variable between 100 – 700 T/day during 1974 – 1991). Most recent (1991) SO_2 emissions may be degassing of magma stranded in upper conduit from previous eruptions	160 T/day (1974 – 1991)	20 years
Rodríguez et al. (2004)	140 – 820 T/day of SO_2 flux recorded over 2-year period. Maximum flux of 820 T/day recorded on 22nd March 2002. Gradual increase in Feb – Mar 2002 related either to increase in magma supply or gradual opening of system through fracture propagation	340 T/day (1999 – 2002)	Intervals over 3 years
Nadeau et al. (2011)	SO_2 flux of 0.12 – 561 T/day recorded during deployment. Avg emission rate 81 T/-day. Summit explosions were frequently followed by increased gas emission	81 T/day (12th, 14th, 21st Jan 2009)	1 - 4 hours over 3 days
Pardini et al. (2019)	Maximum of 207360 T/day recorded (12:30 local time). Minimum estimate of 130 kT SO_2 emitted over 2.5-hr climax	1,248,000 T/day (3rd June 2018)	2.5 hours

Table 15.1: Summary of previous studies of SO_2 degassing at Volcán de Fuego, ordered chronologically.

CHAPTER 16

APPENDIX L: SUMMARY OF OTHER PUBLICATIONS WITH MY CONTRIBUTIONS

This appendix references three academic papers that I co-authored during this project. I have included a link to the publications as well as my contributions.

16.1 Publications

16.1.1 Published papers

- Pardini, F., Queisser, M., **Naismith, A.**, Watson, I. M., Clarisse, L., & Burton, M. R. (2019). Initial constraints on triggering mechanisms of the eruption of Fuego volcano (Guatemala) from 3 June 2018 using IASI satellite data. *Journal of Volcanology and Geothermal Research*, 376, 54-61. `https://doi.org/10.1016/j.jvolgeores.2019.03.014`
  - **Contributions:** Wrote and contributed to Discussion section, including on Fuego's eruptive history to contextualize June 3rd 2018 eruption.

- Wood, K., Thomas, H., Watson, M., Calway, A., Richardson, T., Stebel, K., **Naismith, A.**, Berthoud, L. & Lucas, J. (2019). Measurement of three dimensional volcanic plume properties using multiple ground based infrared cameras. *ISPRS Journal of Photogrammetry and Remote Sensing*, 154, 163-175. `https://doi.org/10.1016/j.isprsjprs.2019.06.002`
  - **Contributions:** Collected image data with NicAIR camera at OVFGO1 (OBS in Table 1).

16.1.2 Papers in review

- Albino, F., Biggs, J., Escobar-Wolf, R., **Naismith, A.**, Watson, I. M, Phillips, J., & Chigna, G. Using TanDEM-X to measure pyroclastic flow source location, thickness and volume: application to the 3rd June 2018 eruption of Fuego volcano, Guatemala. *Manuscript submitted for publication.*
    - **Contributions:** Wrote and contributed to discussion. Contributed images to show change in topography of upper Barranca Las Lajas 2017 - 2019. Collected and refined contextual information on pyroclastic flow development mechanisms observed at Tungurahua (e.g., Kelfoun et al., 2014).

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Using tandem-x to measure pyroclastic flow source location, thickness and volume: application to the 3rd june 2018 eruption of fuego volcano, guatemala.
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