Transitions

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Transitions: comparing timescales of eruption and evacuation at Volcán de Fuego (Guatemala) to understand relationships between hazard evolution and responsive action

Ailsa K. Naismith[1*], Jeremy Phillips[1], Jenni Barclay[1,2], M. Teresa Armijos[3], I. Matthew Watson[1], William Chigna[4] and Gustavo Chigna[5]

Abstract

During volcanic crisis, effective risk mitigation requires that institutions and local people respond promptly to protect lives and livelihoods. In this paper, we ask: *over what timescales do explosive paroxysmal eruptions evolve?* And *how do these timescales relate to those of people's past responses?* We explore these questions by comparing timescales of eruptions and evacuations for several recent events at Volcán de Fuego (Guatemala) to identify lags in evacuation and determine the drivers of these lags. We use multiple geophysical datasets for explosive paroxysmal eruptions ("paroxysms") in 2012–2018 to constrain timescales of eruptive evolution. In parallel, we determine timescales of response and the impacts of uncertainty and eruptive behaviours on decision-making through interviews with institutional and local actors. We then compare eruption and response timescales to explore the drivers for decision-making, whether volcanic, institutional, or personal. We find that eruption and response timescales are comparable. However, we also find that periods of decision-making and warning dissemination delay response until well after eruptive onset. We document how in recent eruptions, response occurs during eruptive climax when risk is at peak. We use paired timelines to elucidate the key drivers of this 'response lag' and show that despite the high levels of forecasting uncertainty, response times could be improved by agreed means to collaborate through shared information and agreed actions. We conclude by considering how the analysis presented here might be useful to different actors who share the goal of preserving lives and livelihoods at Fuego, focussing on how community's needs can be met such that during an eruptive crisis the community can evacuate in time. Our analysis offers practical insights for people working to mitigate risk to populations near active volcanoes around the world.

Keywords Fuego, Timescales, Paroxysm, Response, PDCs, Evacuation, Livelihoods

*Correspondence:
Ailsa K. Naismith
ailsa.naismith@bristol.ac.uk
Full list of author information is available at the end of the article

Introduction

Volcanic eruptions remind us that our natural world is one of constant change and turbulence (Dove 2008). Active volcanoes are agents of both positive and negative change, threatening lives while providing livelihood opportunities to people living on their flanks (Haynes et al. 2008; Donovan 2010). These livelihood opportunities, as well as factors such as place attachment, mean that people often continue to live within the hazard footprint of active volcanoes while being aware of these hazards (Barclay et al. 2019). People have lived with volcanoes for much longer than modern conceptions of natural hazards and volcanic risk have existed (Nomade et al. 2016), and a volcano often represents low threat day-to-day when weighed against other risks (Haynes et al. 2008). As a result, researchers are establishing a new focus on how people can coexist with volcanoes in ways that acknowledge this turbulence while minimizing negative impacts of volcanic hazards (Quevedo Rojas 2001).

One of the most challenging volcanic hazards to anticipate are pyroclastic density currents (PDCs). They are violent hazards fatal to anyone they encounter. Evacuation is expensive and time-consuming, it is disruptive to livelihoods, and it impacts wellbeing (Lavigne et al. 2017; Barclay et al. 2019). However, evacuation is the only action that can protect people from PDCs (Mei et al. 2013; Lavigne et al. 2017) and is thus a necessary disaster risk reduction (DRR) measure that requires communities to be clear of any potentially exposed areas in places of work and living and in evacuation routes. Although at-risk people appear more willing to evacuate where there is greater trust in authorities and previous direct experience of hazard impacts (Johnston et al. 1999), willingness does not necessarily translate to action when a crisis occurs (Wachinger et al. 2013). Evacuation is complex because of its many uncertainties: in forecasting changes in the physical system, in translating forecasts to recommendations for action, and in determining required evacuation time, particularly when communities must be clear of evacuation routes exposed to PDC hazard. During volcanic unrest, sometimes evacuation must be called despite great uncertainty so that people are not in a high-risk area if PDCs do descend.

Fournier d'Albe (1979) argued that: "effective volcanic risk management requires that prediction should cover time intervals comparable with the timescale of human and social responses". Volcanic risk management would therefore be informed by constraining both eruption and response timescales. Timeseries analysis can trace transitions from effusive to explosive activity (Lyons et al. 2010; Delle Donne et al. 2017), and understanding these transitions allows us to assign corresponding levels of risk and therefore decide when protective action (i.e., evacuation) should be taken (Fournier d'Albe 1979). Meanwhile, studying evacuation timescales can shed light on the time a community needs to organize and leave a high-risk area, including situations where communities proactively evacuate without waiting for an evacuation order. Studying evacuation timescales at Volcán Tungurahua reveals that people have thresholds for risk tolerance that are meaningful to their own experience and can make decisions that integrate information from authorities (Armijos et al. 2017). There is great value in comparing timelines of eruption and response to reveal how different actors make decisions regarding volcanic risk and point to what lessons may be learned before the next eruption (Mei et al. 2013; Syahbana et al. 2019; Jumadi et al. 2020). Modelling of evacuation processes also shows the value of comparing eruption and response. At Volcán El Chichón (Mexico), Marrero et al. (2013) present evacuation not as a single action but as a series of dependent steps that must be completed before eruptive climax. Minimizing the factors that prolong these steps is essential to improving response time during crisis (Marrero et al. 2013).

Volcán de Fuego (hereafter Fuego) is an active stratovolcano in Guatemala that stands at 3768 m asl. Fuego's eruptive activity has been documented in written records since 1524. Occasional periods of quiescence occur between prolonged periods of low-intensity background activity (consisting of slow lava effusion and discrete Strombolian and ash-rich explosions that occur 4–12 times per hour) and occasional higher-intensity explosive paroxysmal eruptions ("paroxysms", VEI 2–4), in which lava flows grow rapidly and summit explosions become almost continuous (Naismith et al. 2019). Fuego has been consistently active since a VEI 2 eruption on 21st May 1999 (GVP, 2023). This volcano typically has 3–4 paroxysms per year, with the exception of a four-year gap in 2008–2012 and a 3.5-year period (beginning in 2015 and ending with the 3rd June 2018 eruption) in which paroxysms occurred almost monthly (Naismith et al. 2019). Fuego's paroxysms frequently generate PDCs that rapidly descend Fuego's seven major *barrancas* (drainage ravines). Both the steeper, near-summit portion of ravines and their shallower regions where people cross are called "barranca" by people around Fuego (a use which we follow in this paper) and are all recognized as areas of high PDC risk: on 3rd June 2018 PDCs descending Barranca Las Lajas overspilled its confines and destroyed the community of San Miguel Los Lotes (Ferrés and Escobar-Wolf 2018).

Previous work provides some constraints on the timescales of paroxysmal activity at Fuego. (Rodríguez et al. 2004) traced the evolution of a single eruption that took place between January–August 2002. Magma arrived at surface in January 2002, filling Fuego's summit crater and in February overspilling into a lava flow that continued to grow until July. An increase in summit explosions occurred in February–March (from 75/day to 400/day) and again in June–July, associated with Vulcanian activity and peak lava flow length (Rodríguez et al. 2004). Paroxysms in 2005–2007 evolved much faster: precursory activity (accelerating explosions and lava effusion), paroxysmal climax, and decline occurred in 24–48 hours (Lyons et al. 2010). Paroxysms in 2015 occurred monthly (an eruptive cycle twice as fast as that of 2005–2007) and started coincidently with lava effusion (Castro-Escobar 2017). During an accelerating paroxysmal cycle in 2015–2018, eruption onset and acceleration to climax happened in a few–48 hours (Naismith et al. 2019; Aldeghi and Escobar-Wolf 2019). Eruptive onset during this period was defined by the national scientific monitoring agency (INSIVUMEH, or *Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología*) in Guatemala City based on rapidly increasing RSAM and visual observations from around Fuego. Occasionally, paroxysms have unfolded even more rapidly – e.g., the 3rd June 2018 eruption developed over ~16.5 hours (INSIVUMEH Special Bulletin #033-2018), with a climactic phase lasting 2.5 hours (Pardini et al. 2019). However, this eruption was somewhat atypical (Pardini et al. 2019), and more recent eruptions (23rd – 24th Sep 2021, 7th - 8th Mar 2022) have similar timescales to ones before 3rd June 2018 (GVP, 2023). Excepting a few common features (most paroxysms in 2005–2015 were preceded by lava effusion and lasted 24–48 hours), paroxysmal activity varies greatly and many questions remain regarding how these events begin and evolve, and consequently what are the monitored signals associated with paroxysmal evolution.

Fuego is monitored by INSIVUMEH at their main office in Guatemala City and their observatory (OVFGO, *Observatorio del Volcán de Fuego*) located in the village of Panimaché Uno on Fuego's SW flanks.[1] This monitoring coexists with a network of volunteer civil protection groups (COLREDes, or *Coordinadora Local para la Reducción de Desastres*) managed by the national civil protection agency (CONRED, *Coordinadora Nacional para la Reducción de Desastres*) through its subsidiary office (DPV, or *Departamento de Prevención en Volcanes*; formerly UPV), located in Antigua Guatemala. Since the 3rd June 2018 eruption, the COLRED network has increased in number and capacity (Prevention Web 2019). The Fuego COLRED network (as of 24/08/2023) includes 25 communities and 2 *fincas* (privately-owned farms). Figure 1 is a map produced by CONRED that shows Fuego, local communities, and eight official evacuation routes. Evacuation is particularly complex at Fuego because paroxysms tend to generate PDCs in multiple barrancas, and many of the evacuation routes cross these barrancas (see Fig. 1). Other barriers that inhibit evacuation include lack of resources and insufficient communication with authorities (Escobar Wolf 2013; Naismith et al. 2020). Despite these challenges, communities have successfully evacuated several times in recent years. Paroxysms associated with widespread evacuations are 13th September 2012, 3rd June 2018, 19th November 2018, 7th March 2022, and 5th May 2023 (*E. barrios*, pers. comm.) (see Table 1).

At Fuego, evacuation is envisaged as a voluntary, community-led movement, in which the decision to leave is made by all community members and advised by institutions, rather than the forced removal of people from their property by the military or law enforcement. When Fuego's activity increases, INSIVUMEH produces a Special Bulletin combining visual observations from OVFGO with satellite and seismic data compiled in Guatemala City. INSIVUMEH sends Special Bulletins directly to DPV, who add more information and simplify the language so that the bulletins are more comprehensible to communities around Fuego. DPV then sends the revised bulletins to COLREDes in each community. The COLRED must convene their community at the designated emergency meeting point to hear the contents of the bulletin. The community must then decide whether to evacuate or not. This decisión involves the community development council (COCODE, *Consejo Comunitario de Desarrollo*). DPV is legally responsible for communicating bulletins to COLREDes, and COLRED members are legally responsible for informing their communities. To protect COLREDes from potential legal issues if community members who decide not to evacuate are later impacted by volcanic hazards, a COLRED who unites their community during eruptive crisis must share a document called an "Acta": residents unwilling to evacuate must sign the Acta declaring they absolve the COLRED of responsibility should they be harmed by volcanic hazards by staying. The COLRED must also complete a full list of residents who wish to evacuate and send this list to DPV. This list informs DPV of the number of evacuees, and therefore the amount of transport required. Once DPV has a list of evacuees from a community, they coordinate buses to visit that community to transport evacuees to shelters. This is the current evacuation process at Fuego and was most recently realized in the paroxysm of 5th May 2023 when communities on Fuego's SW flanks evacuated. We will refer to this complicated process as "community-led evacuation" in this paper and debate its

[1] INSIVUMEH briefly employed an observer for Fuego's SE flanks between 2019 and 2021. There is currently no INSIVUMEH observer for this side of Fuego.

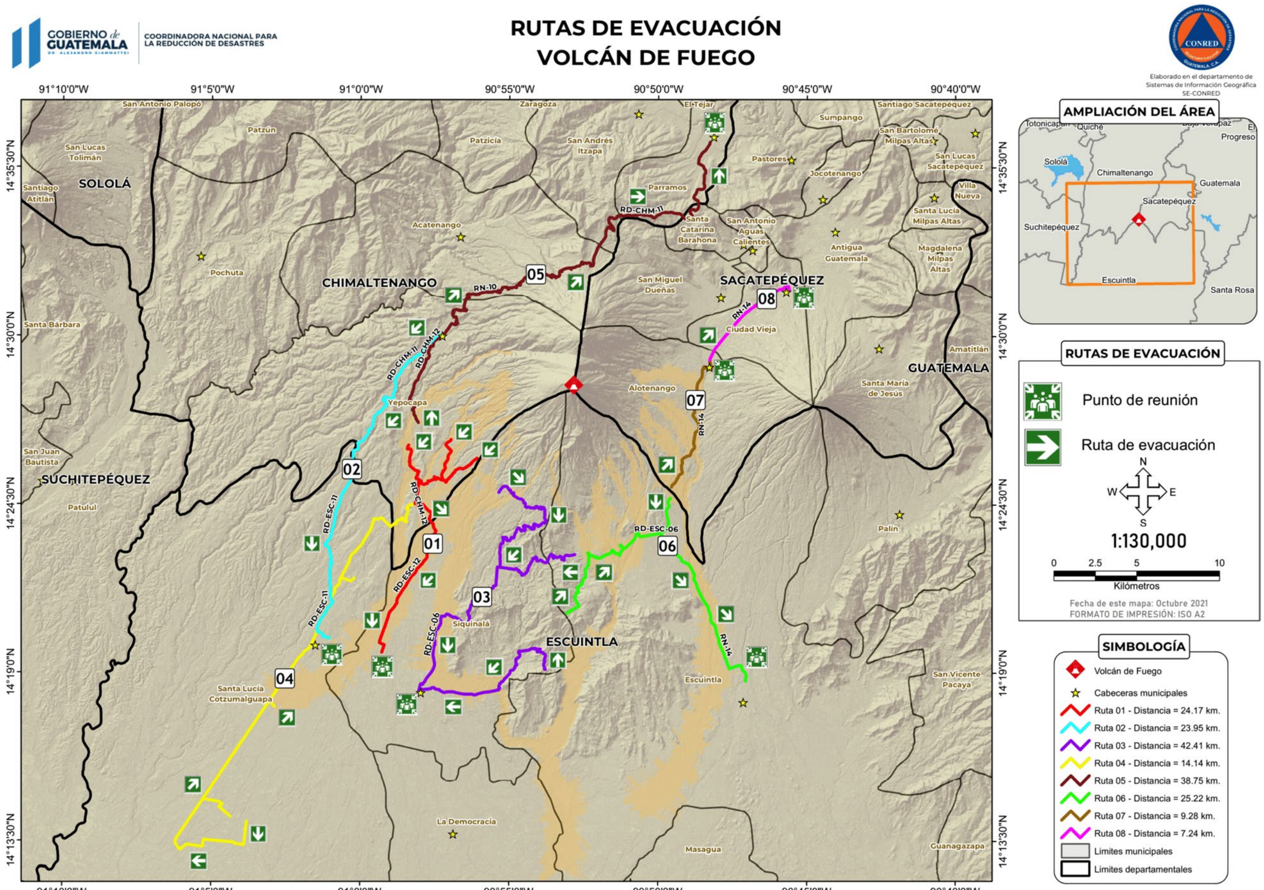

Fig. 1 The eight evacuation routes for communities around Fuego (CONRED 2022a). Route 1 (red) crosses Barranca Taniluyá; Route 3 (purple) crosses Barranca Ceniza; Route 4 (yellow) crosses the Pantaleón river (via a high pedestrian bridge); Route 5 (burgundy) crosses Barranca Seca/Santa Teresa (residents of Sangre de Cristo only); Route 6 (green) crosses Barrancas Trinidad and El Jute, the Las Cañas river, and the Guacalate river (via highway); Route 7 (ochre) crosses Barranca de Agua and Barranca Honda (via highway). Individual maps of the eight evacuation routes are available at (CONRED 2022b)

implications in "Understanding the drivers and processes of community-led evacuations".

This paper explores eruptive evolution and human response to provide insights into available evacuation time during volcanic crisis. We explore these issues by asking two questions: *Over what timescales do explosive paroxysms of Fuego evolve?* and, *how do these timescales relate to those of peoples' past responses and evacuation actions?* To address these questions, we structure our paper as follows: (1) constrain timescales of paroxysm at Fuego; (2) constrain timescales of response for several groups of actors; (3) pair timescales of paroxysms and actors' responses to understand the processes and relationships involved in response to paroxysm; (4) compare these real paired timescales to idealized timescales to identify core drivers of gaps between these timescales and to understand where future research and risk mitigation could focus. Exploring these questions provides insights into past responses to volcanic crises at Fuego and affords understanding of possible responses in future. We end by discussing how the knowledge we present in this paper could be relevant to local actors with a common goal of preserving lives and livelihoods during eruptive crisis.

Methods

Analyzing timescales of eruption

We used several datasets to make multiparametric timeseries of four eruptive events (three paroxysms and one effusive eruption) in 2015–2018 (Fig. 2). We use these as archetypes to represent comparable paroxysms occurring since Fuego's reactivation in 1999, and for comparison with previous studies of this period (Table 1). We included volcanic radiative power (VRP) values (measurements of the heat radiated by volcanic activity at the time of a satellite acquisition) from the MIROVA system (Coppola et al. 2020) and real-time seismic amplitude measurements (RSAM) from

Table 1 An overview of eruptions relevant to this study. **Top:** summary of previous studies that give eruption timescales since Fuego's reactivation in 1999. **Bolded text** refers to precursory activity; text in parentheses indicates the activity the timescale relates to. Middle: paroxysms since 1999 associated with widespread evacuations. **Bottom:** eruptions described in this study include five paroxysms and one effusive eruption

Eruption timescales since 1999 from previous studies			
Period	**Timescale**	**Description**	**Reference**
Jan – Aug 2002	7.5 months (eruption)	Arrival of magma at surface; elevated Strombolian activity; lava flow effusion; Vulcanian activity; declining activity	Rodríguez et al. (2004)
Aug 2005 – Jun 2007	24–48 hours (paroxysm)	**Gas chugging evolving into continuous explosions; precursory lava effusion** lasting until end of paroxysm; climax with sustained fire fountain and lava flows; declining activity	Lyons et al. (2010)
Mar 2014 – Oct 2015	Up to 48 hours	**Precursory increase in RSAM**; paroxysms coincident with start of lava effusion and characterised by Strombolian explosions.	Castro-Escobar (2017)
Jan 2015 – Jun 2018	24–48 hours (climax)	**Precursory lava effusion, increasing RSAM, and accelerating explosions**; climax; declining activity	Aldeghi and Escobar-Wolf (2019); Naismith et al. (2019)
3rd June 2018	16.5 hours (eruption); 2.5 hours (climax)	Rapidly accelerating explosive activity and PDC generation; climax with tall ash plume and series of PDCs; decline in activity	IB #033–2018; Pardini et al. (2019)
23rd – 24th Sep 2021, 7th – 8th Mar 2022	32–48 hours	**Precursory lava effusion and increasing seismicity**; climax with sustained lava effusion and PDCs; decline in activity	GVP, (2023)
Paroxysms since 1999 associated with widespread evacuations			
Date		**Description**	**References**
13th Sep 2012		Evacuation of 5–10,000 people from SW flanks of Fuego, led by OVFGO observers from Panimaché Uno	Cruz Roja (2012); Herrick (2012); INSIVUMEH (2012); this study
3rd Jun 2018		Preventative evacuation of La Reunión golf resort; evacuation of communities around Fuego after PDCs descend on Los Lotes	CONRED (2018a); Ferrés and Escobar-Wolf (2018)
19th Nov 2018		Evacuation of several communities (including Panimaché Uno) coordinated by CONRED and emergency services	GVP, (2023); this study
7th – 8th Mar 2022		Government-supported evacuation of 522 residents from three communities (Morelia, Panimaché Dos, Panimaché Uno)	Bartel and Naismith (2023); GVP, (2023)
5th May 2023		Evacuation of ~ 1200 residents from six communities W/SW of Fuego	France24 (2023); GVP, (2023)
Eruptions described in this study			
Date		**Description**	
13th Sep 2012		VEI 3 paroxysm producing PDCs and widespread evacuation	
28th – 30th Jul 2016		Paroxysm producing lava effusion and PDCs	
27th – 29th Sep 2016		Paroxysm producing lava effusion but no PDCs	
5th Nov 2017		Effusive eruption not evolving to paroxysm	
3rd Jun 2018		VEI 3 paroxysm producing PDCs that buried a community	
19th Nov 2018		VEI 2 paroxysm producing PDCs and provoking evacuation	

INSIVUMEH (also presented in Naismith et al. (2019)). We supplemented these with new data of SO_2 fluxes measured by a multispectral camera, NicAIR (Prata and Bernardo 2009) that was deployed at the La Reunión golf resort between 2016 and 2020. A full description of how NicAIR data were processed and analysed appears in Naismith (2021).

We found only certain events were suitable for study due to limited data availability. Before June 2018, INSIVUMEH had few resources to monitor Fuego's activity (Roca et al. 2021). For ~8 years the only permanent monitoring equipment was a single seismometer, FG3. In this period, RSAM from FG3 and visual observations of the volcano from the three INSIVUMEH observers at

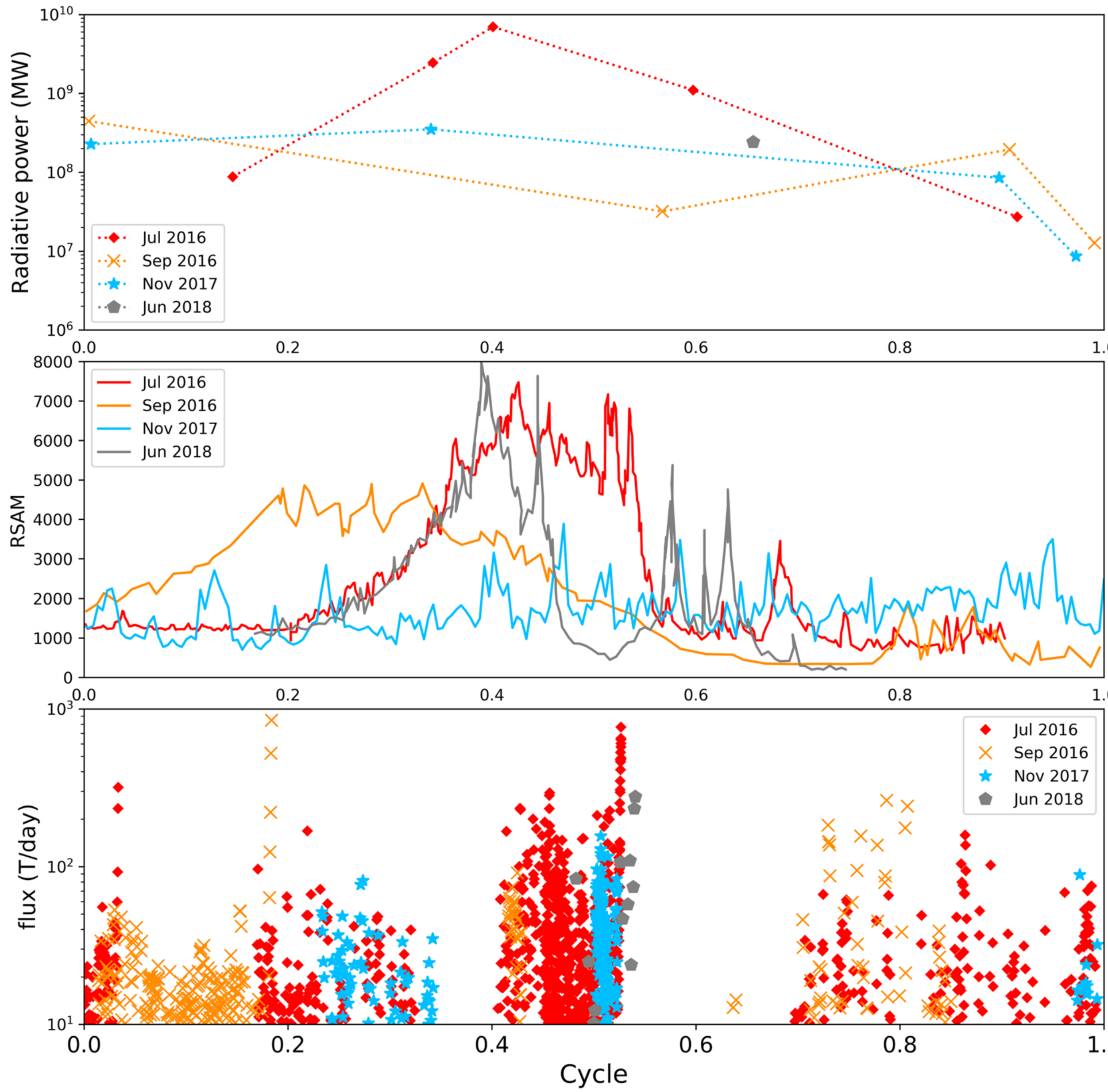

Fig. 2 Graphs show values of MIROVA (top), RSAM (middle), and SO_2 (bottom) for the four eruptions of Fuego in 2015–2018 studied in this paper. Note that x-axis is not time but stage of eruptive cycle, where 0 = onset of eruption and 1 = end of eruption (start and end determined from INSIVUMEH Special Bulletins). Details of each eruption appear in correspondingly named sections and stages of eruption appear in Fig. 4

OVFGO were the primary data with which INSIVUMEH forecasted short-term changes in eruptive behaviour. Additional data from MIROVA and NicAIR allow us to explore paroxysms in greater detail, but these instruments' coverage during the period of study was inconsistent for several reasons including cloud cover. The events captured in greatest detail are July and September 2016, November 2017, and June 2018, which is why we chose them for this study (see SM-1 in Supplementary Material). "Timescales of eruption" section presents VRP, RSAM, and SO_2 datasets for these four eruptions, normalized for the length of each eruptive cycle to aid comparison of eruptive behaviour between events (following Watson et al. (2000)). We also pair VRP, RSAM, and SO_2 datasets with INSIVUMEH Special Bulletins that describe Fuego's activity (including eruption onset and end, lava effusion, and changes in explosivity) to give more detailed descriptions of each event.

Understanding the drivers and processes of community-led evacuation

Information on evacuations at Fuego is often scarce, limited to brief CONRED reports and news articles. The exception is the eruption of 3rd June 2018, which received extensive coverage due to its tragic outcome. We built timescales of response by re-analysing the interviews previously presented in Naismith et al. (2020). Demographic data and analysis methods are consistent with Naismith et al. (2020). As in that work, our results here are based on two studies using in-depth interviews conducted in 2018 and 2019 in which interviewees were recruited by a mixture of purposive and 'snowball' sampling (Atkinson and Flint 2004; Palinkas et al. 2015). Interviews were already transcribed and available in NVivo for this study; we performed thematic analysis guided by the analytical approaches presented in Pistrang and Barker (2012). This work was approved by the University of Bristol Research Ethics Committee (Project ID 5117) and consent was obtained from all study participants.

We used semi-structured interviews to gain a range of stakeholder's views about not only the timing and sequencing of actions and decision-making during evacuation but also how they explain their actions, or delayed actions. Interview data allowed us to constrain response timescales in general, although interviewees of course used specific exemplars to illustrate their point of view, and the view of individual interviewees may not fully represent the views or actions of a community or organization. Nonetheless, interviews allowed us to understand how decisions were being made by communities because this method of data collection provided a source of detailed, rich information on response timescales that would otherwise be unobtainable. We also make comparisons between communities' response timescales that are contingent on geographic location and access to resources and information. Our interview results mostly focus on the communities of Panimaché Uno and San Miguel Los Lotes. We recognize that this influences the experiences of evacuation at Fuego, and take care to consider the limitations this sampling has on our results and discussion. We also include quotations from interviews with officials from INSIVUMEH and CONRED, to understand the role of scientific uncertainties and communication in the community-led evacuation process.

Pairing of eruption and response timescales

We then paired eruption and response timescales to explore intersections between them and to discuss the implications of these intersections for risk to local people. Here we were able to explore in detail eruptions for which our constructed datasets were sufficient to allow us to make direct comparison between volcanic activity and social responses (including actions of authorities and monitoring agencies). Not all paroxysms with good monitoring data coverage resulted in evacuation; some paroxysms which provoked evacuation had poor monitoring data coverage. We chose the paroxysms of 13th September 2012 and 3rd June 2018 for study of paired eruption and response timescales for their better data coverage, the widespread evacuations they caused, and the frequency with which people mention these eruptions spontaneously in interview, showing their prominence in collective memory.

Results and discussion

Timescales of eruption

Eruptions of Fuego evolve differently over a range of timescales. Figure 2 summarizes VRP and RSAM values and SO_2 fluxes for three paroxysmal and one effusive eruption in 2015–2018, using datasets described in "Methods: Analysing timescales of eruption". Vertical axes for VRP values (top subplot) and SO_2 fluxes (bottom subplot) use a logarithmic scale to permit the large range in values between different eruptions to be plotted together. The horizontal axis is not time but cycle, where 0 = start of eruption and 1 = end of eruption (determined from INSIVUMEH bulletins announcing start and end of eruption). The timing of all VRP, RSAM, and SO_2 values for each eruption have been normalized to fit within that eruptive cycle. Insufficient monitoring data and bulletins for the 13th September 2012 paroxysm prevents our including it in this section; instead, we present an approximate eruption timescale in "Paired timescales: September 2012".

RSAM values for all paroxysms plotted in Fig. 2 rise and fall during eruption, while the effusive eruption of November 2017 is associated with consistent values of RSAM (middle subplot). Reselecting an eruptive cycle by RSAM (0 = start of RSAM increase and 1 = end of RSAM increase) shows a greater similarity between the three paroxysms (Fig. 3). This similarity may be useful to investigate for determining mechanism(s) for triggering paroxysms at Fuego; mechanism(s) which so far remain elusive. However, this investigation is beyond the scope of this paper. INSIVUMEH bulletins announce paroxysm at the same time or earlier than RSAM acceleration for the eruptions we study. Subsequent results and discussion of eruption timescales (Fig. 4, and following five sections) are based on Fig. 2.

To illustrate the different behaviours and timescales of Fuego's eruptions, we describe below in more detail the eruptions plotted in Fig. 2. We describe the three paroxysms chronologically (July 2016, September 2016, June 2018) before describing the effusive eruption of November 2017. Relevant INSIVUMEH Special Bulletins are

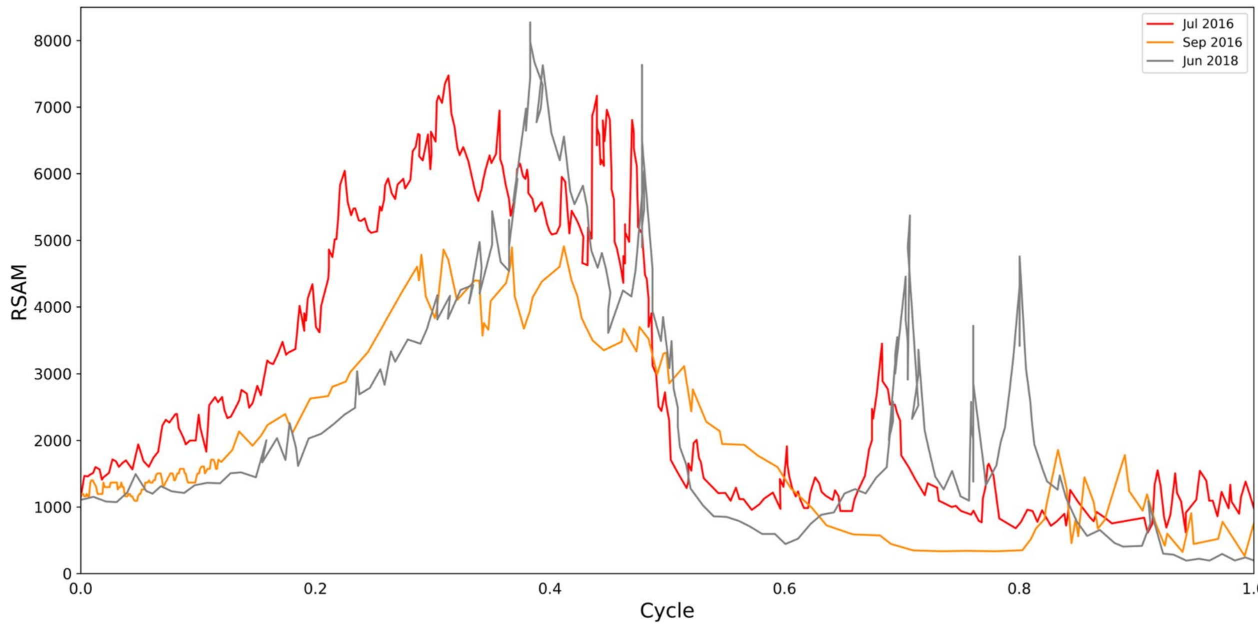

Fig. 3 Plot of RSAM values for three paroxysmal eruptions of Fuego in 2015–2018 studied in this paper. RSAM values are the same as for Fig. 2 middle subplot, but x-axis is different: 0 = onset of RSAM acceleration and 1 = end of RSAM acceleration (start and end determined from INSIVUMEH Special Bulletins)

referred to as (IB #NUM-YEAR). Times are local unless stated otherwise.

July 2016

INSIVUMEH reported the beginning of a Strombolian eruption at Fuego at 12:00 on 28th July 2016. Frequent ash explosions fed an eruptive column reaching 5.5 km asl, and lava fountaining reached 500 m above Fuego's crater (GVP, 2023). Continuing summit activity through 28th July fed two lava flows in Barrancas Santa Teresa and Las Lajas that reached 1.5 and 3 km, respectively. Activity increased on 29th July as the first PDC descended Barranca Santa Teresa at 12:00, followed by several more; PDCs descended until 14:30 (IB #141–2016). On 29th July, the day of eruptive climax, the Washington VAAC recorded a maximum plume altitude of 6.7 km asl, while MODVOLC reported 17 thermal anomalies (GVP, 2023). RSAM is elevated over a 16-hour window (22:00 on 28th July – 14:00 on 29th July), including Strombolian activity (12:00–00:00 on 29th July), acceleration (00:00–08:00), climax (08:00–14:30), and descent (15:00–00:00) (see Fig. 2). The paroxysm lasted ~48 hours (GVP, 2023).

September 2016

An increase in lava fountaining and effusion began on 24th September (IB #177–2016). On 25th–26th September, incandescent activity dropped but heavy rainfall produced lahars in several barrancas. Increasing explosive activity on 27th September led INSIVUMEH to declare the beginning of an eruption at 07:30 (IB #180–2016). Explosion rates, lava fountain height, and lava flow length continued to grow during the day (IB #182–2016). At 16:10 on 27th September there were two active lava flows in Barrancas Las Lajas (1500 m) and Santa Teresa (1800 m). The latter reached a maximum length of 2000 m at 21:00, coinciding with greatest height of lava fountaining (300 m above summit) and most frequent explosions (IB #183–2016). This is the approximate time of paroxysmal climax. Activity declined throughout 28th September and the eruption finished after 36 hours (GVP, 2023).

Timeseries do not evolve in parallel in this paroxysm (see Figs. 2 and 4). 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).

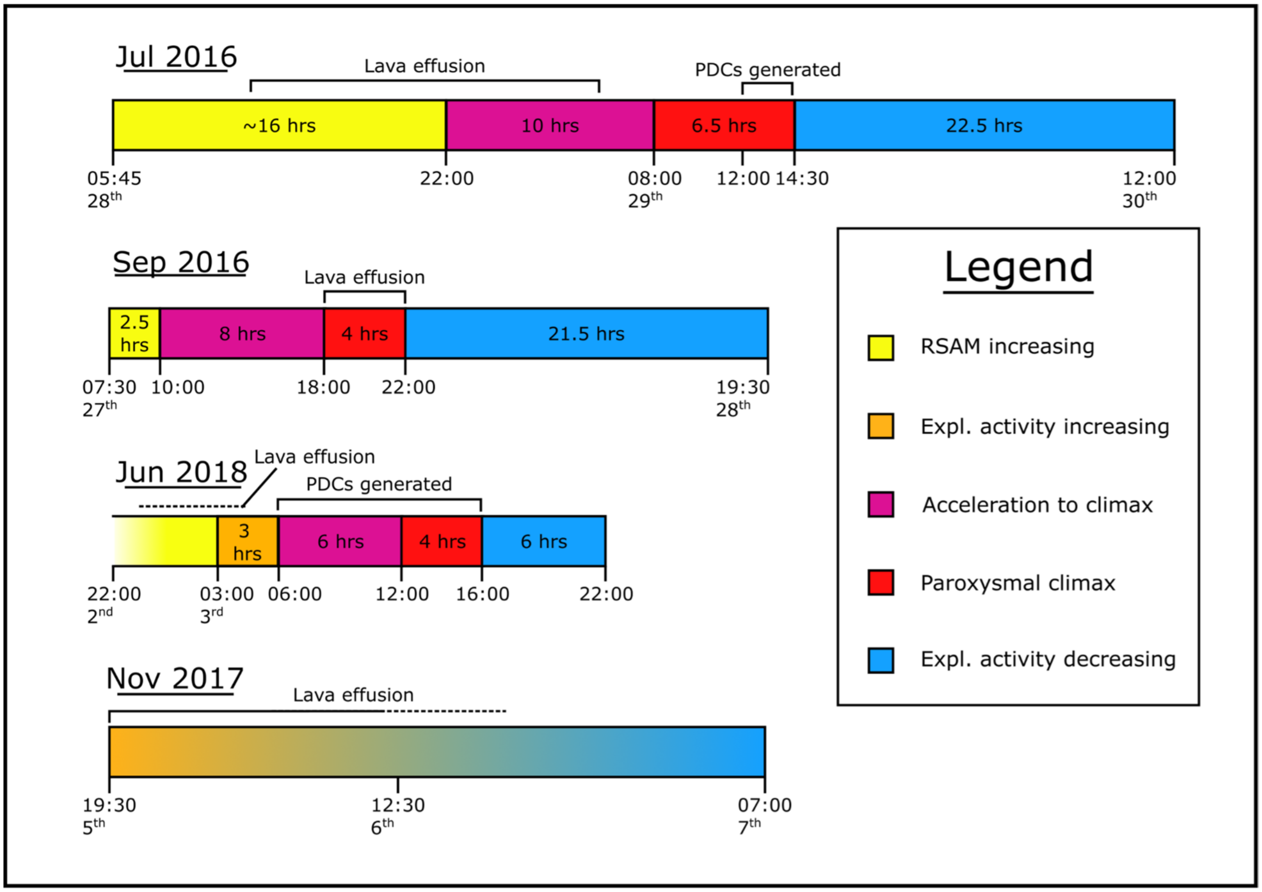

Fig. 4 Timescales of eruption for four eruptions (three paroxysmal and one effusive) of Fuego in the 2015–2018 eruptive cycle. Eruptions are the same as those plotted in Fig. 2. Transitions between eruptive styles and related times are derived from INSIVUMEH Special Bulletins. Paroxysmal climax periods are constrained by times given in Special Bulletins. The three paroxysms show large behavioral differences, for example in the duration of increased explosivity and if/when PDCs are generated. The November 2017 effusive eruption was distinct in not producing a sharp uptick in RSAM, although like the paroxysms it did produce lava flows and like the September 2016 paroxysm it did not produce PDCs

June 2018

INSIVUMEH reported an increase in Fuego's explosive activity at 06:00 on 3rd June 2018 (GVP, 2023). A series of PDCs descended Barranca Santa Teresa at ~07:00; because the summit was covered by cloud, they were detected once they descended below the clouds. The Washington VAAC reported an eruptive plume reaching 9 km asl at 11:30. La Reunión, located beside Barranca Las Lajas, evacuated between 10:30 and 12:00. By 13:40, PDCs had descended in all barrancas except Trinidad (IB #029–2018). The most devastating series of PDCs descended Barranca Las Lajas at ~15:00, likely associated with some collapse of the upper flanks of Fuego (Albino et al. 2020). These PDCs surpassed the barranca capacity and overspilled, sweeping away the Las Lajas bridge and burying Los Lotes at ~15:10 (Ferrés and Escobar-Wolf 2018). 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. A PDC descended Barranca Las Lajas at 19:30 on 5th June (GVP, 2023).

Inclement weather and equipment failure hindered data capture and consequently assessment of timescale over which activity evolved. This is representative of the challenges in monitoring volcanoes in this context (Roca et al. 2021). Cloud cover prevented satellite capture of Fuego's summit that might have captured acceleration to paroxysm. Of INSIVUMEH's two functioning seismometers (FG3 and FG8), only FG3 was online, and became so saturated with data that it ceased transmitting (Alvarez 2019). Nevertheless, timescales can be estimated from INSIVUMEH bulletins. Paroxysm began at ~06:00 with strong explosive activity and PDCs (IB #027–2018). PDCs continued through the morning and early afternoon (IBs #028–2018 and #029–2018, 10:00 and 13:45), intensifying mid-afternoon with the destruction of Los Lotes. Activity decreased during the evening. INSIVUMEH announced the end of eruption at 22:00 (IB #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 (see Fig. 2).

November 2017

INSIVUMEH reported an increase in activity on 3rd November 2017 and declared the start of an effusive eruption on 5th November at 19:30 (IB #170–2017). At this time, Fuego was producing 6–8 explosions per hour, an eruptive column reaching 4600–4800 m asl, and two lava flows towards Barrancas Santa Teresa (1000 m) and Ceniza (600 m). Continuous lava fountaining on 5th and 6th November fed the lava flows, which reached 1200 m (Santa Teresa) and 800 m (Ceniza) at 12:30 on 6th November (IB #173–2017). INSIVUMEH announced the end of the eruption at 07:00 on 7th November, reporting that lava flows had become inactive, and that Fuego was producing 6–8 explosions per hour and an eruptive column reaching 4600–4800 m asl (IB #175–2017). Total eruption time was 36.5 hours (constrained by IBs #170 and #175–2017). Unlike the three paroxysmal eruptions, this eruption did not contain a climactic explosive phase producing PDCs. The eruption is traced by a steady increase in RSAM values, rather than rapid acceleration of RSAM for the three paroxysms.

From the above information, we can estimate timescales for several eruptions at Fuego (Fig. 4). Although multiparametric datasets can give greater confidence in identifying onset of acceleration from background activity to a paroxysm, the inconsistent association between acceleration onset and monitored signals (Figs. 2 and 4) shows that surface observations continue to be important in forecasting paroxysm. Figure 4 also shows that PDCs can develop at any point during paroxysm: late stage (July 2016), beginning early and continuing (June 2018), or not at all (September 2016).

Discussion – timescales of eruption

A particular challenge for forecasting paroxysm at Fuego is the lack of clear geophysical indicators of effusive-to-explosive transition. The three paroxysms we study were preceded by rapid increase of RSAM and lava effusion (Figs. 2, 3 and 4). RSAM increase and lava effusion are precursory signals of paroxysm documented by many other authors (Lyons et al. 2010; Castro-Escobar 2017). Interview data suggest the 3rd June 2018 eruption was also preceded by lava effusion, which had not been documented before (Naismith et al. 2019). Our study of eruption timescales also reveals a "stalled" paroxysm on 5th November 2017, where eruption did not complete an effusive-to-explosive transition and RSAM did not accelerate in days before eruption. Other timeseries data are even less strongly correlated with paroxysmal onset, and thus difficult to use as a reliable forecasting tool. Although further volcanological research could elucidate the drivers of paroxysmal events, and thus improve forecasting, there will always be some uncertainty associated with a volcanic system (Sparks 2003). Recent studies on volcano observatory best practices note the importance of reducing uncertainty as much as possible, and advise data and experience sharing between observatories and multidisciplinary studies of individual volcanoes as means to reduce uncertainty (Pallister et al. 2019).

Understanding the drivers and processes of community-led evacuations

Interviews with local people and officials from INSIVUMEH and CONRED reveal the processes and the relationship between warning messages and decision-making during evacuations in response to paroxysms. The processes that interviewees describe often relate to multiple eruptions, so we do not present results by eruption. Instead, we present quotations that relate to key stages in the evacuation process. This allows us to build understanding of the drivers and processes involved when a community leads its own evacuation. The three stages of community-led evacuation we report on are: (1) **warning dissemination**; (2) **decision-making**; and (3) **evacuation**.

Warning dissemination

Some communities (including Panimaché Uno) have direct sight of Fuego, allowing them to make visual observations. All communities (whether they have direct sight of the volcano or not) expect to receive information on Fuego's activity via INSIVUMEH bulletins. An official explains how dissemination of warning messages during eruptive crisis is intended to inform a community's decision to leave, without requiring officials to travel to the community:

> *Official 5: We issue a communication, addressed to the population, so that they make decisions and take precautions, so if there is a need for self-evacuation, they should not wait for our instructions, but make their own decision if they see that the phenomenon is threatening the population and their lives.*

Another official admitted that these messages often do not reach their intended audience: "...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 ... [the bulletins] reach a certain population, but to those people for whom it matters that it arrives, it doesn't arrive." Officials are aware that there are communication breakdowns, and in recent years have physically travelled to communities to deliver these warning messages (e.g., 19th November 2018, 7th – 8th March 2022). These visits to communities also involve officials in the decision-making process (see following section). This journey takes several hours. An official compares how fast officials can reach a community from Antigua Guatemala with the speed of PDCs:

> *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 3rd June 2018, travelled from the crater to around 7 km below in more or less seven minutes.*

Decision-making

Once warning messages are received, a community gathers to collectively make the decision to evacuate or not. Below, a resident of Panimaché Uno describes their community's decision to evacuate from a paroxysm. Triangulation with other interviews and INSIVUMEH bulletins suggest this was the 19th November 2018 paroxysm. They consider eruption onset to be 20:00 and beginning evacuation 6 hours later, at 02:00, after consultation between the community's COLRED and COCODE:

> *Resident of Panimaché Uno: That time we left at 2 in the morning, yes, we managed to leave that time.*
> *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 powerful. It started at around 8 at night, growing stronger. It was 9, 10, and grew stronger, enthusiastic, 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 … if we wanted to leave, and we said yes.*

An official recalls a similar consultation in Panimaché Uno for the 5th May 2023 paroxysm, that produced PDCs in Barranca Ceniza. In this paroxysm, the official recalls consultation at Panimaché Uno beginning at 06:00 once PDCs began to descend and continued until 15:30 when the community decided to evacuate. We spoke to people from other communities who described the same type of meeting, confirming that this period of consultation is intrinsic to the community-led evacuation process at Fuego. Many people also said that CONRED staff have travelled to communities to participate in the decision-making process:

> *Interviewer: And have you evacuated many times?*
> *Resident of Panimaché Uno: Yes, we have evacuated, we have evacuated.*
> *Interviewer: How do you get out?*
> *Resident: Ah, you see, CONRED comes, and they come to authorize that they take us, and they take us in buses, or else they have to take us by truck.*

Evacuation

After warning messages are communicated and the decision to evacuate is made, the evacuation itself may begin. Residents gather essential documents and clothes for their stay in shelters and await the arrival of buses that CONRED have ordered. Once the buses have arrived and people have boarded, the journey to the shelters begins. A resident of Panimaché Uno estimates the time needed to travel from their community to an evacuation shelter in Santa Lucía Cotzumalguapa (see Fig. 1):

> *Interviewer: How long would it take to get to Santa Lucía from here?*
> *Resident of Panimaché Uno: 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.*

People at Fuego have experience of unsuccessful evacuations, often due to impassable routes. An official describes an unsuccessful evacuation attempt by Panimaché Uno residents on 3rd June 2018:

> *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. But a lahar did not let them pass. And they had to turn back.*

Interviews make clear several key stages (warning dissemination, decision-making, and evacuation) in community-led evacuation at Fuego. From the data, we can draw a schematic timeline for the whole evacuation process (Fig. 5). The process begins with a period of warning, which a community gathers from INSIVUMEH bulletins and (where possible) from their own observations. INSIVUMEH warning messages increase in intensity and frequency in parallel with eruptive activity. When warning messages are received, a community gathers to discuss the situation and decide

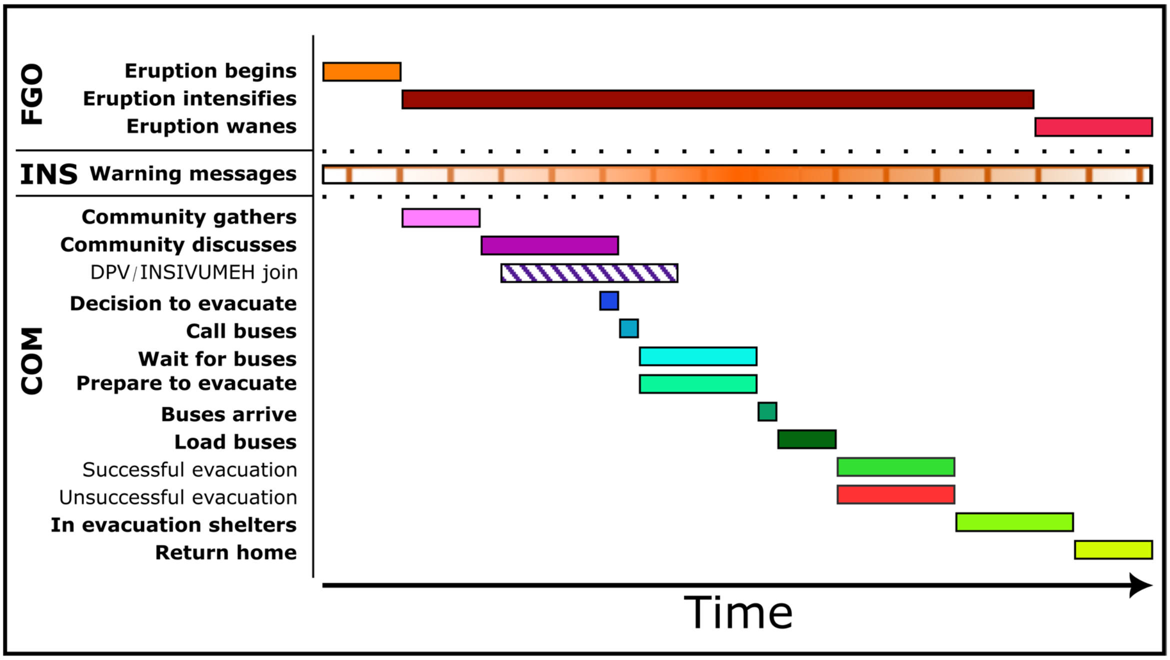

Fig. 5 Schematic of the community-led evacuation process for a community evacuating from eruptive crisis of Fuego. Schematic includes dependent steps (e.g., "Load buses" begins once "buses arrive" has ended). **FGO** means Fuego's activity, **INS** institutional messages, and **COM** steps involving the community. Steps that may or may not occur (i.e., DPV/INSIVUMEH join, success of evacuation) are shown in regular (i.e., not **bold**) font

whether to evacuate. This decision is made with a community's COCODE and involves communication with INSIVUMEH and CONRED. Sometimes, a community may prolong the decision-making process to wait for INSIVUMEH and/or CONRED staff from Antigua or Guatemala City. Once a decision to evacuate has been made, transport is required. Some vehicles may be available within the community, but often outside resource is needed. Recently, buses have been loaned from sugar-cane plantations (*ingenios*) located on the coastal plains south of Fuego. People must wait for the buses to arrive and gather their families and essential belongings in preparation for time in evacuation shelters. Once the buses arrive, there is a loading period, then more time is needed to drive to the shelter. This drive takes 40–60 minutes for Panimaché Uno but varies considerably for other communities (see "Discussion - Paired timescales").

Although Fig. 5 is an evacuation timescale based primarily on interview data from Panimaché Uno, it can be adapted for other communities around Fuego. We estimate an evacuation timescale of 6–10 hours for Panimaché Uno. This estimate is corroborated by a resident of Panimaché Uno, who describes the whole evacuation process of 19th November 2018. They estimate that evacuation took ~10 hours, from beginning of paroxysm at 19:00 on 19th November to arrival at Santa Lucia at 05:00 the following morning, having left Panimaché Uno at 03:30:

> *Resident of Panimaché Uno: 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 coordinated. INSIVUMEH issued bulletins informing the emergency services of the eruption - firefighters, army, CONRED, municipalities, and communities, through CONRED's DPV. 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 and 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.*

Discussion – understanding the drivers and processes of community-led evacuation

Interviews allowed us to draw a schematic timeline of a community-led evacuation process at Fuego (Fig. 5). Most interview data relate to Panimaché Uno. Panimaché Uno has challenges and advantages unique among Fuego's communities. On one hand, it is one of the closest communities to Fuego's summit (~7 km SW), so it is both within the reach of multiple hazards and more remote from evacuation shelters and safety. On the other hand, the community has the presence of OVFGO and its trained observers, constant communication with INSIVUMEH's central office, and a clear view of Fuego. With these advantages (comparable to those of the La Reunión golf resort), it might be expected that Panimaché Uno residents decide to evacuate more readily than other communities. However, we find that in recent paroxysms, residents of Panimaché Uno have decided to evacuate only after a collective decision-making process lasting several hours. Although interviewees recall this process happened with great consensus in the 19th November 2018 paroxysm, it is possible that the recent tragedy of 3rd June 2018 heightened people's sense of risk and facilitated the decision to evacuate.[2] Subsequent crises that do not happen immediately after a volcanic disaster may be less strongly associated with heightened volcanic risk, and consensus to evacuate within a community may be less easy to achieve. Previous studies conducted when Fuego is not in paroxysm show that local people do normalize Fuego's persistent eruptive activity to some degree (Graves 2007; Naismith et al. 2020). Among Fuego's communities, Panimaché Uno has been the most frequent to evacuate since the volcano began its current eruptive regime in 1999, with at least five evacuations (Table 1). Given this extensive previous experience of evacuation and the advantages stated above, why does evacuation at Panimaché Uno continue to take so long? Furthermore, would timescales of response be larger for other communities which do not have the advantages that Panimaché Uno has? This may have serious implications for encountering risk along the evacuation route ("Discussion - Paired timescales" section).

In the "Understanding the drivers and processes of community-led evacuations: Evacuation" section, we show that in recent paroxysms, CONRED staff have attended community meetings to share warning messages and assist in decision-making. Because staff may have to travel to communities from Antigua Guatemala or Guatemala City, this could prolong the decision-making process and further delay evacuation by several hours. Both the collective decision-making process and waiting for the arrival of CONRED staff increase the time that a community remains in an area of high risk as Fuego's activity intensifies. The delay also means that people evacuate during the most dangerous part of eruption. This delay may have implications for future eruptive crises. For example, if a community decides to wait for the arrival of CONRED staff to decide to evacuate, but staff are unable to reach the community, the community may delay the decision to evacuate while eruptive activity accelerates. Many communities are located within the PDC hazard zone, and as we have described, PDCs may develop at any point during a paroxysm. Delay of evacuation could increase exposure of a community to PDC hazard. There is some thinking to be done on how communication between officials and locals in the current community-led evacuation process could be strengthened.

Beyond Fuego, timescales of response to eruption are affected by (1) communication failures between authorities (Macías and Aguirre 1997); (2) stakeholder differences in hazard perception (Tobin and Whiteford 2002); (3) breakdown of telecommunication systems (Voight 1990); (4) lack of an adequate emergency plan (Lechner and Rouleau 2019); (5) lack of community structure to efficiently enact the evacuation plan. In general, tackling these reduces response time. Informed by an evacuation timescale for each community (including the constituent segments that contribute to the whole), it would be helpful to explore each of these factors in depth to consider a community's needs regarding evacuation and whether these needs are likely to be met in an eruptive crisis. We present an initial framework to do so at the end of this paper.

Paired timescales

September 2012

INSIVUMEH bulletins and literature inform timescales of eruption and response for the 13th September 2012 paroxysm. Fuego previously had a small paroxysm with PDCs on 3rd–4th September (Ramos 2012). The 13th September 2012 paroxysm was preceded by 48 hours of increasing seismicity and lava effusion in Barranca Ceniza (INSIVUMEH 2012). INSIVUMEH announced an eruption at 04:00 on the 13th, and by 07:15, an eruptive plume had reached 2 km above Fuego's crater (INSIVUMEH 2012). At 07:30, CONRED increased the Alert Level from Yellow ("Prevention") to Orange ("Danger") (Herrick 2012). PDCs descended barrancas

[2] 3925 people were evacuated in the 19th November 2018 paroxysm (GVP, 2023). Fuego had another paroxysm producing PDCs on 12th October 2018 (IB #177–2018); however, only 62 people evacuated from Sangre de Cristo and Palo Verde. In November, PDCs descended in multiple barrancas and reached greater runout lengths, which may explain why more people evacuated than in October 2018 – the next PDC-producing eruption after 3rd June.

from 09:00 (INSIVUMEH 2012), prompting CONRED to raise the alert level to Red ("Emergency") at 09:12 for communities SW of Fuego (INSIVUMEH 2012). This alert level instructs people to evacuate danger zones and to follow instructions emitted by authorities (CONRED 2021). The eruption escalated rapidly: at 09:47, a series of PDCs descended Barrancas Las Lajas and Ceniza (Escobar Wolf 2013). Observers at OVFGO reported that the PDCs travelled 7.6 km in three minutes (INSIVUMEH 2012). Ash in this area reduced visibility to 2–3 m (Herrick 2012). Previous paroxysms since Fuego's reactivation in 1999 had produced PDCs that primarily descended Barranca Santa Teresa and caused the evacuation of Sangre de Cristo; the descent of PDCs in Barranca Ceniza to a distance close to communities was unexpected by people in Panimaché Uno. Although the director of CONRED stated that it could be necessary to evacuate as many as 33,000 people (Expansion Mx 2012; Arrecis 2018), the actual number of evacuees was between 5000 (Ferrés and Escobar-Wolf 2018) and 10,600 (Cruz Roja 2012). Although some sources suggest that CONRED ordered an evacuation (Arrecis 2018), interviews in this paper and other survey sources (Escobar Wolf 2013) indicate that communities on Fuego's SW flanks spontaneously evacuated immediately after the descent of PDCs at 09:47. The decision to evacuate Panimaché Uno was made through consultation in OVFGO between members of the community, OVFGO observers, and volcanology staff in INSIVUMEH (via radio). Women, children, and elderly people from Panimaché Uno evacuated with a bus owned by another resident of Panimaché Uno; the bus's load caused it to break down on route, and evacuees waited in the road while CONRED organized trucks hired from the nearby *ingenio* Pantaleón to pick up evacuees and complete their evacuation to Santa Lucía Cotzumalguapa. The communities that evacuated included Morelia, Panimaché Uno, Panimaché Dos, and Sangre de Cristo (INSIVUMEH 2012). Such a widespread evacuation had not occurred since 1999, and official shelters were not available. Instead, temporary evacuation shelters were set up in two primary schools at Santa Lucía Cotzumalguapa. Evacuated families were requesting water for consumption (Cruz Roja 2012). By the afternoon of the 13th, seismicity decreased, fewer PDCs descended, and summit explosions grew less frequent. CONRED had reduced the alert level to Orange by 15:00 on 13th September (Cruz Roja 2012). INSIVUMEH reported that the eruption had begun to wane by 10:00 on 14th September (CONRED 2012). Evacuated people returned to their homes throughout 14th September, many due to overcrowding and lack of water. People returning earlier travelled by their own means, while those returning later were assisted by the Guatemalan army and firefighters. Interestingly, INSIVUMEH's summary report for this eruption explicitly constrains PDC onset: "pyroclastic flows ... as a general rule are generated 3–4 hours after an eruption has started" (INSIVUMEH 2012). These events are plotted in Fig. 6.

We draw additional information from our interview data. An OVFGO observer recalled how the decision to evacuate Panimaché Uno was made: "I called INSIVUMEH and said, 'Here I am. Anything you need, we are ready.' ... I stayed. And the COCODE came … I said [to them], 'No, gentlemen, let's leave.' ". Below, an official confirms that Panimaché Uno spontaneously evacuated and describes the conditions of the evacuation shelters:

> *Official 1: Very few people evacuated from Morelia. But Panimaché evacuated, and they arrived at some schools in Santa Lucía. But ... there was not much knowledge of evacuation. So, what they did was only leave people in the shelters. But they did not attend to them. And the people who talked to me about how they had fared with the evacuation complained that they had been abandoned in the schools. And that many schools didn't even have water […] At least, for INSIVUMEH I think it was a success. In the sense that the observers held a very important role in the evacuation. They coordinated the evacuation of the people of Panimaché. CONRED waited for them in the Pantaleón school. I think that since then, people believe a great deal in the observatory.*

Residents of Los Yucales and San Andrés Osuna (Fig. 1) describe timescales of eruption and evacuation for their respective communities:

> *Resident One of Los Yucales: 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: 2012, it was large. I was going to Escuintla when they started to call me.*

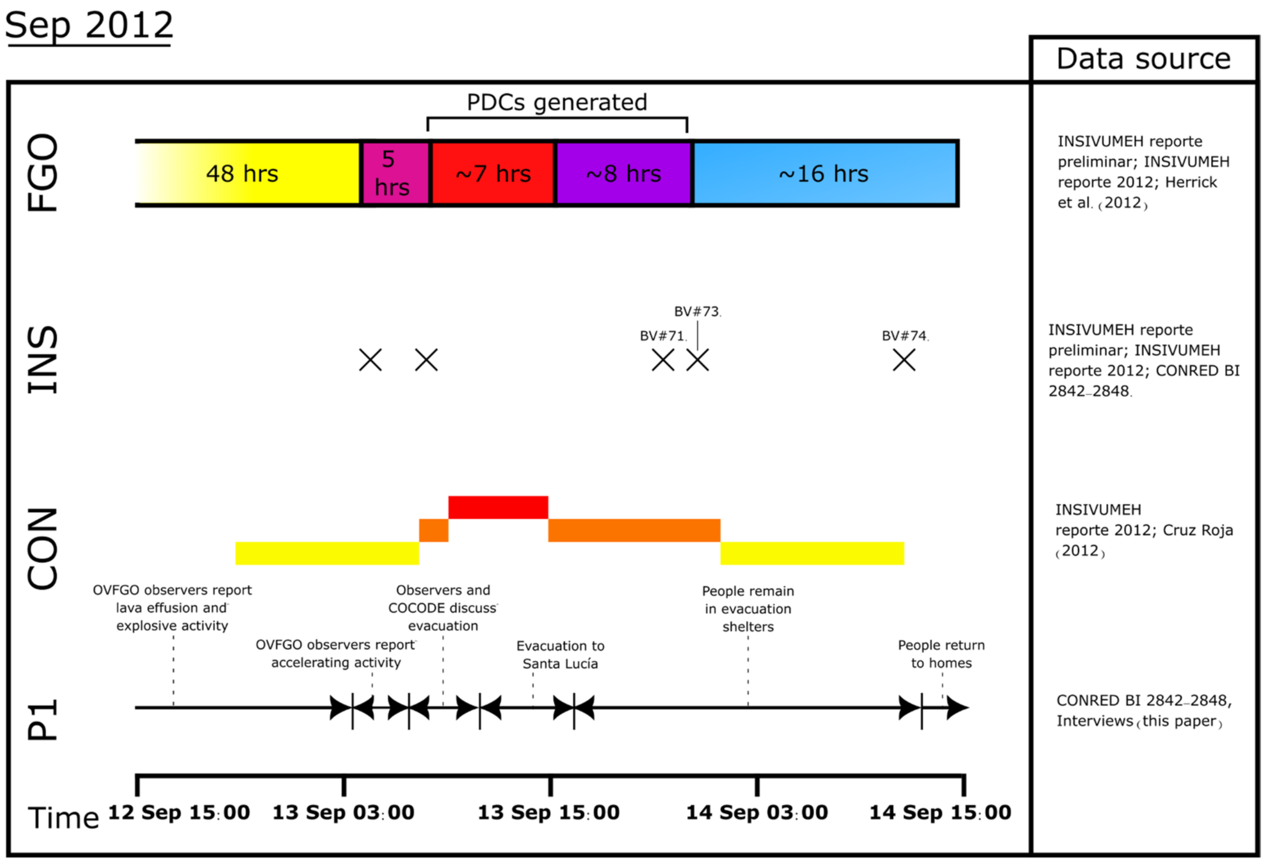

Fig. 6 Comparing timescales of eruption and response for the 13th September 2012 paroxysm, including eruptive behaviour (**FGO**), INSIVUMEH bulletins (**INS**), CONRED alert levels (**CON**), and evacuation process for Panimaché Uno (**P1**). Legend for **FGO** is same as in Fig. 4, except for purple which indicates ongoing PDC generation and explosions. INSIVUMEH Special Bulletins appear as crosses. INSIVUMEH released at least 12 Special Bulletins for the eruption, but these are not directly available (where possible, information from them was derived from CONRED Boletines Informativos 2842–2848). CONRED alert levels are given for communities S and SW of Fuego

... I had to return, for my daughters. And I came, and it was completely dark. At [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 quite a long time because it started at around 11 in the morning, maybe. And at around 4 in the afternoon, it calmed down.

Using these data, we can create a paired timescale for this eruption. Five hours passed between INSIVUMEH announcing beginning of eruption (04:00) and first descent of PDCs (09:00). Communities decided to evacuate soon after PDCs descended rapidly (09:47) and some had completely evacuated by 14:45, as they were requesting water in Santa Lucía Cotzumalguapa (Cruz Roja 2012). Thus, on 13th September 2012 the whole process of evacuation happened in ~5 hours. (This could be used to inform the Fig. 5 schematic.) Figure 6 is a paired timescale that includes eruptive evolution of Fuego, information from INSIVUMEH and CONRED, and the evacuation process for the community of Panimaché Uno. Unlike for June 2018, most interviewees who talked about 13th September 2012 were from Panimaché Uno, so our response timescale is for only one community.

June 2018

Figures 2 and 4 and the previous "June 2018" section summarize the eruptive activity of 3rd June 2018, so we will not repeat it here. We instead build on this summary with data from interviews with both officials and local people that constrain eruption and response timescales and elucidate the processes and relationship between warning messages and decision-making during this eruption. Because this eruption received more widespread coverage than 13th September 2012, we can trace response timescales for multiple communities on 3rd June 2018. Below, an official describes their efforts to deliver warning messages:

Official 4: And we were … from the morning, making outings, and we were at the Las Lajas bridge from 12:30, making coordinations, because it was necessary that there were not only people in the office but also in the field, giving information.

The official then goes on to explain how fast PDCs descended that day:

Official 4: [My companion] got to the bridge before the flow descended. And when we saw that it was descending towards the bridge, we left … I went to drop her at her community … and I came back. When I returned to Los Lotes, the pyroclastic flow had already arrived … We didn't know that it was going to change direction and jump out of there.
Interviewer: And this was – at what time in the afternoon?
Official 4: At 3 o'clock exactly was when it started to descend towards the bridge. And I spent about 10 minutes in going to drop her off, and I returned to Los Lotes. And already the flow was arriving.

Another official gives a vivid account of both eruptive processes and community actions throughout the day, noting that information was limited by poor weather conditions, instrumental failure, and communication challenges (including scarce communication with communities on Fuego's SE flanks):

Official 1: The eruption began at approximately 03:00. [OVFGO] called me at 05:00 and told me, "Look, there are pyroclastic flows descending already". … We received no data from the seismic station since about 12 or 15 hours before. We could see absolutely nothing. The volcano was completely covered by cloud […] [first] there was a very large lava flow, which one could see below the clouds. And then pyroclastic flows started to descend, principally in Barranca Seca [Santa Teresa] … at the beginning [we] thought it was just another eruption. We didn't know the magnitude […] Hours passed, and until about 10 o'clock, there were no seismic records. […] around 10:00, I started to receive calls that ash was falling in the Chimaltenango area. […] around 11:30 in the morning, [someone] called me and told me, "From the satellite images I can see that the eruptive column is 16,000 metres high". And I said, "[Damn], this is one of the big eruptions, not a little one". And in the bulletin we put that this was the largest eruption since 1974. And that it was possible that it would produce pyroclastic flows in all barrancas. However, we continued seeing pyroclastic flows only in Barranca Ceniza. But we estimate, after seeing the records, that … the climax of the eruption was … between 11:30 and 2 in the afternoon, approximately … the observer started to report pyroclastic flows in Ceniza, too. Big ones […] however, I didn't get a single call from the other flank. That they were saying that in La Reunión pyroclastic flows were already descending.
Interviewer: Pardon, did they call, or not?
Official: No, they didn't call. No-one informed me. Even though on the side of La Reunión, they almost descended – at the same time they descended in Ceniza, they descended in La Reunión. At around 12:35. […] It wasn't until [someone] called me to say: "Pyroclastic flows are descending in La Reunión". But this was already at 2:30, 3 […] and at around 3:10, without knowing, I called a police officer from La Reunión … and they told me that in that moment they were helping the people who had died or been hurt on the bridge. Then we started to see the videos that rapidly started to appear online. And then … we saw the magnitude of the event. […] And over the course of hours we started to hear that the pyroclastic flow had overtaken Los Lotes.

Figure 7 shows a paired timeline of eruption and response for 3rd June 2018, constructed from multiparametric datasets, INSIVUMEH bulletins, and interview data. As for Fig. 6, we include Fuego's activity, information from INSIVUMEH and CONRED, and community response. INSIVUMEH's first bulletin appeared at 06:00 (IB #027–2018). Their next bulletin (IB #028–2018) appears at 10:05 and reports PDCs descending in Barrancas Santa Teresa and Ceniza. Visibility is too poor to determine length of the PDCs. INSIVUMEH issues a third Special Bulletin at 13:45 (IB #029–2018), reporting PDCs in all of Fuego's major barrancas except Trinidad and El Jute and recommending that CONRED consider evacuating people from Sangre de Cristo. Bulletin IB #030–2018, released at 14:00, affirms this is the strongest eruption of recent years. Bulletin IB #031–2018 (16:55) reports that PDCs continue descending the same barrancas, and that lahars have begun to descend in the Pantaleón and Mineral rivers. Interestingly, this bulletin reports that "the communities of Sangre de Cristo, Finca Palo Verde, Panimaché, and others have been evacuated to shelters by CONRED", which may either contradict the official's testimony ("Understanding the drivers and processes of community-led evacuations: Evacuations" section) or suggest that Panimaché Uno attempted evacuation twice.

A summary report provides information on CONRED's coordination with communities and local government on 3rd June (CONRED 2018a). The alert level for

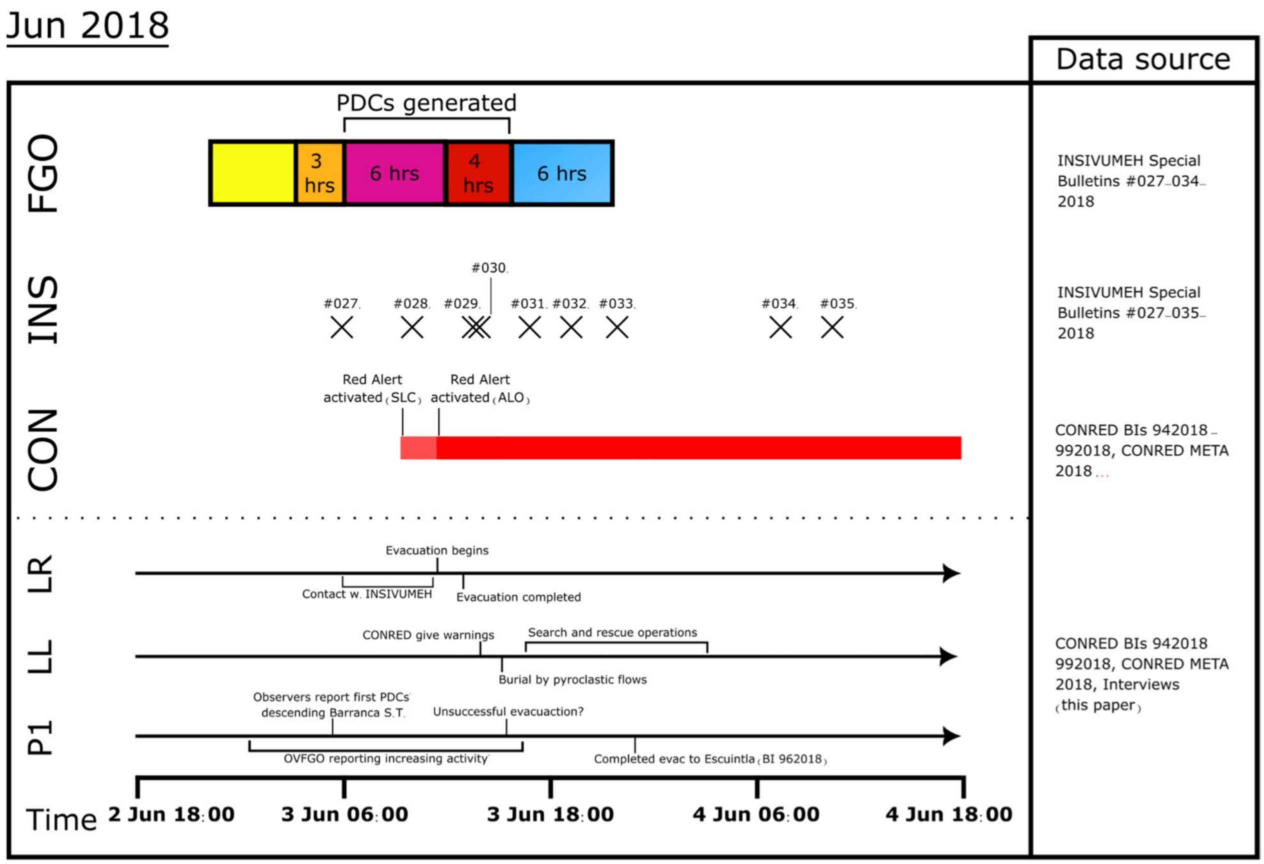

Fig. 7 Paired timeline of eruptive activity and response for three geographically separated communities for the 3rd June 2018 paroxysm, including eruptive evolution (**FGO**), INSIVUMEH bulletins (**INS**), CONRED alert levels (**CON**), and evacuation process for Panimaché Uno (**P1**), San Miguel Los Lotes (**LL**), and La Reunión (**LR**). Timeline illustrates how variable the response to paroxysm can be among different communities

Fuego was raised to "Red" at 09:25 for the municipality of Santa Lucía Cotzumalguapa (responsible for hosting evacuees from Fuego's western flanks) and at 11:00 for the municipality of Alotenango (responsible for evacuees further east) (CONRED 2018a). However, at 11:00 CONRED were publicly recommending that evacuation was not necessary (CONRED 2018b). La Reunión began to organize evacuation of its staff and guests at ~10:30. San Miguel Los Lotes was destroyed at ~15:10 (Ferrés and Escobar-Wolf 2018). We estimate that the time available to Los Lotes to complete evacuation was ~9 hours, from INSIVUMEH's first Special Bulletin at 06:00 (IB #027–2018) to the community's destruction at ~15:10.

Discussion – paired timescales

Paired timescales allow us to compare eruptive evolution and human response in Fuego's recent paroxysms (Figs. 6 and 7). For the 13th September 2012 paroxysm, both eruption evolution and community response were strikingly rapid. Interview and bulletin data suggest that PDCs took 5–40 minutes to travel from Fuego's summit to Panimaché Uno, while evacuation took ~5 hours ("Paired timescales: September 2012" section). Evacuation took longer both on 3rd June 2018 (9 hours ("Paired timescales: June 2018" section) and in subsequent paroxysms where the at-risk population had recent knowledge of disaster (e.g., ~9 hours for 19th November 2018). Why have decision-making and evacuation taken longer in subsequent paroxysms? The official quoted at length on page (16) shows that a breakdown in communications was partly responsible for the response lag on 3rd June 2018 (as in (Voight 1990)). And the official quoted on page (11) suggests that Panimaché Uno's decision to evacuate was not motivated by PDCs descending since 05:00, but by news of the destruction of Los Lotes at 15:10. Thus, the response lag might also be attributed to differences in hazard perception (Tobin and Whiteford 2002). Although in the immediate aftermath of the 3rd June 2018 disaster, some people appeared more willing to evacuate, this effect seemed to diminish even by 2019 (Naismith et al. 2020). In future crises not preceded by volcanic disaster, other factors may have more control on response timescale.

Paired timescales are a useful tool to understand a central challenge of evacuation at Fuego: crossing barrancas. In "Understanding the drivers and processes of community-led evacuations: Evacuation", we show the key stages involved in evacuation (Fig. 5). We also show that evacuation may be curtailed by volcanic flows cutting off evacuation routes. People at Fuego may encounter greater risk while evacuating than remaining if they traverse an area when flows (PDCs or lahars) might be descending. PDCs and lahar hazards have different implications for evacuation timescales. Figure 8 shows two evacuation routes (red and purple) from Fig. 1 superimposed on a preliminary PDC hazard map created by INSIVUMEH's Volcanology Department after the 3rd June 2018 disaster (INSIVUMEH et al. 2018). Residents of Panimaché Uno evacuating via the red route must cross Barranca Taniluyá to Santa Lucía; successful evacuation via this route takes 40–60 minutes by vehicle or ~2.5 hours on foot. PDCs travel much faster, meaning that they could arrive in Panimaché Uno and reach that community's crossing point at Barranca Taniluyá faster than the evacuation time. These scenarios would have devastating consequences for both people who chose to stay behind in Panimaché Uno and people who chose to evacuate along this route after onset of eruption. Similarly, residents of the community of San Andrés Osuna (population ~ 3270) must evacuate via the purple route (Fig. 8) which crosses Barranca Ceniza, another area of high PDC hazard. Fuego's PDCs can travel long distances (e.g., 11.7 km from summit in Barranca Las Lajas and 8.5 km from summit in Barranca Ceniza in the 3rd June 2018 paroxysm (Ferrés and Escobar-Wolf 2018)). This challenge holds for many other communities we have not included in Fig. 8 (e.g., Panimaché Dos and Morelia must cross Barranca Taniluyá; Ceilán, Chuchú and La Rochela must cross Barrancas Ceniza and Trinidad; and El Zapote must cross Barranca El Jute). In the case of a paroxysm that rapidly accelerates and produces PDCs in multiple barrancas, none of these communities will be able to escape via their evacuation routes if they decide to leave.

Lahars travel slower than PDCs and they are not always produced during paroxysm. However, Guatemala's heavy rainy season (May – September) and abundant pyroclastic deposits means that lahars are a major barrier to evacuation if Fuego has a paroxysm in the rainy season. Lahars have previously reached crossing points in Barranca Taniluyá (this paper), occurred extensively after paroxysm in Barranca Las Lajas (Dualeh et al. 2021), and destroyed a Scout encampment in Barranca Ceniza at a distance from Fuego's summit beyond the crossing point for the Osuna evacuation route (Naismith et al. 2020). It is difficult to create an evacuation route at Fuego that does not require a community to cross a barranca to safety. At-risk communities have built footbridges to cross barrancas, but these are slow and dangerous to cross. Consequently, lahars greatly increase evacuation timescales during the rainy season. Although at-risk communities have criticized the Guatemalan government for failing to build new vehicle bridges over barrancas or to rebuild bridges destroyed by lahars, a lack of bridge infrastructure remains a problem at Fuego (Paredes 2018; Garcia and Montenegro 2021). For timely evacuation, it may be instructive to consider eruptive scenarios that generate a sufficient volume of PDCs to reach these critical points on evacuation routes, and to construct similar scenarios for lahars. We suggest that future studies could work backwards from dynamic model simulations or observations of PDC and lahar velocities to identify how much time a community needs from the first step of evacuation (Fig. 5) to crossing the barranca on their evacuation route, i.e., completing enough of the evacuation process to be beyond the high-hazard zone when PDCs/lahars descend. Given that our study focusses on paroxysms since 1999 (which caused eruptive crises of a limited range of scales), subsequent studies could also consider the time required to evacuate from a future larger eruptive crisis of Fuego. A crisis of this scale may not have occurred in recent history, so may be beyond the experiential knowledge of local people; however, it would almost certainly require additional risk awareness education and evacuation planning. If knowledge of larger events cannot be drawn from historical experience, scientific knowledge of prehistoric events can provide. Approaches such as downward counterfactual analysis (Aspinall and Woo 2019) could, by considering alternative evolutions of past eruptions, inform understanding of the range of scenarios that could result in impacts and provide insights valuable to local and official actors. There is a shared goal of learning from disaster to avoid repeating the tragedy of 3rd June 2018 in "taking people unaware":

> *Official 4: When we went past Los Lotes, we went past warning people, with siren on and everything. I didn't see a single person leave. Nobody, nobody. That is, nobody expected that ... perhaps they imagined that, from some source or other, it could have escaped, and if it had come from the road. But they never imagined that from behind them ... it was going to come out.*

Despite the dangers we express in the previous paragraph, we acknowledge that uncertainties in forecasting eruptive activity and difficulties in communicating this uncertainty to at-risk communities continue to inhibit timely risk mitigation action at Fuego (Fig. 7). Forecasting

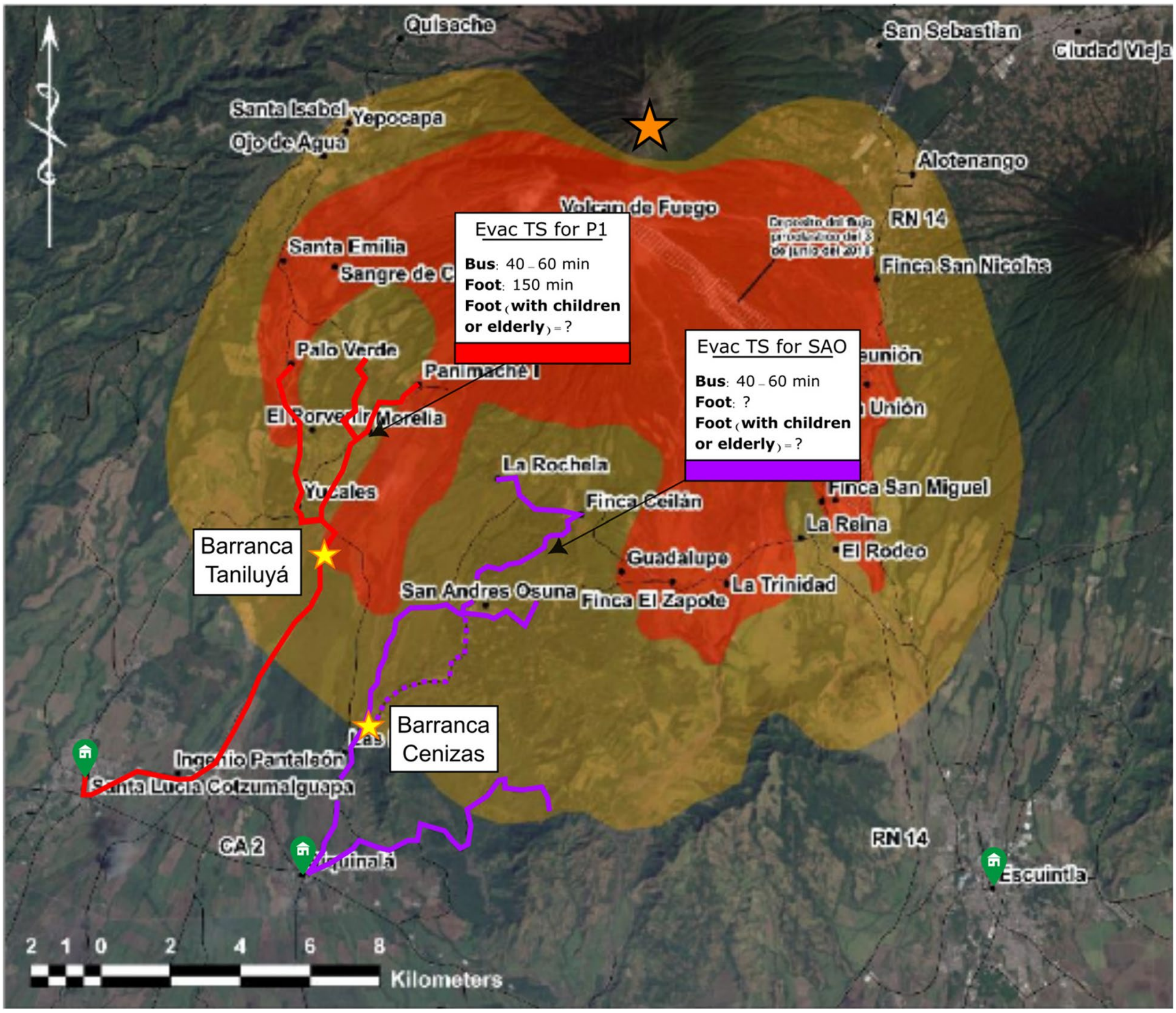

Fig. 8 Two evacuation routes from Fig. 1 superimposed on a preliminary PDC hazard map produced by INSIVUMEH together with external collaborators after the 3rd June 2018 disaster (INSIVUMEH, 2018). Red route is for several communities including Panimaché Uno to evacuate to Santa Lucía Cotzumalguapa; evacuation timescales are for Panimaché Uno. Purple route is for several communities including San Andrés Osuna to evacuate to Siquinalá; evacuation timescales are for Osuna. PDC hazard map shows areas of high (red) and moderate (yellow) PDC hazard. Stated evacuation timescales are for evacuation during dry season; evacuation during rainy season would likely be prolonged or curtailed due to the greater possibility of lahars descending and reaching the evacuation route where it crosses a barranca

uncertainty could be diminished (and consequently response timescale shortened) by identification of geophysical signals that forecast eruption with more confidence. However, while INSIVUMEH's monitoring capacity has greatly improved since 2018, response timescales have not decreased. Conversely, forecasting uncertainty can be amplified by instrumental failure and cloud cover ("Results and discussion: June 2018" and "Paired timescales: June 2018" sections), both of which are lived problems at many volcanoes with limited resources. INSIVUMEH do occasionally communicate uncertainty in Special Bulletins (e.g., *"there is still poor visibility of the volcanic edifice, so that it is not possible to observe the length of the [pyroclastic] flows"* – IB #028–2018, 10:05 on 3rd June 2018). But how is this uncertainty interpreted by local people? The official we quote above appeared to believe that warnings were poorly understood or not received by locals. Is this still the case? Future work should find this out – but we must also allow that timely action necessarily involves some uncertainty. Evacuation should happen not only when hazard impacts are inevitable, but also when the situation is too uncertain for people to stay. Perhaps evacuation was so fast on 13th September 2012 in part because locals had not previously experienced such an eruption and were too uncertain to wait for officials to decide to leave. The different responses of locals and officials to the 13th September 2012 paroxysm also bears comparison to other case studies where eruptions emphasized the differences between how different actors do or do not integrate volcanic perturbation into their lives (Dove 2008; Armijos et al. 2017).

Our study shows the complex communication between local and official actors during eruptive crisis at Fuego. The relationship between experience, knowledge, and life-preserving action is well established in the volcanological literature for other locations where experience influences action (Favereau et al. 2018). It is important to recognise that on the timescale of a human lifetime any community may not experience the full range of likely activity at that volcano and so collaborations with officials (including monitoring and civil protection agencies) can provide integrated degrees of experience (Mothes et al. 2015; Barclay et al. 2019). However, this collaboration also poses challenges in the case of the community-led evacuations at Fuego. Officials suggest this evacuation process was adopted after the experience of 13th September 2012, and built trust between communities and OVFGO ("Paired timescales: September 2012" section) – but the evacuations themselves have sometimes created a dependency on both direct conversation with officials and on the 'body language' of seriousness of the situation associated with their arrival ("Understanding the drivers and processes of community-led evacuations: Evacuation" section) as the communities' experience of eruptive events has increased. Waiting for officials to arrive conflicts with several assumptions implicit in community-led evacuation: that local people have the information necessary to decide to evacuate without officials being present; that locals have the resources necessary to enact that decision; and that it is preferable to evacuate earlier and with greater uncertainty than it is to wait and bring more people into a high-risk zone. These assumptions show that community-led evacuation is a difficult undertaking at Fuego. DPV maintains communications with 25 at-risk communities and two at-risk fincas around Fuego; visiting even a few during eruptive crisis is an impossible task. However, asking locals to lead their own evacuation without the confidence of official presence (as the official quoted on page (10) suggests) also seems difficult. These opposing difficulties illustrate a key issue in evacuation at Fuego: the continuing lack of clear agreement on who is responsible for evacuation decision-making (Naismith et al. 2020). We suggest there is some learning that can be done on taking action despite uncertainty with direct conversation between actors in places with community-based monitoring (Mothes et al. 2015; Andreastuti et al. 2016; Armijos et al. 2017).

Paired timescales also show that while calling evacuation earlier will allow for timely response, it will also increase the possibility of false alarms. Paroxysms are often preceded by 12–24 hours of accelerating activity (Figs. 2 and 4). If evacuation takes 5–12 hours to complete ("Paired timescales – September 2012" and "Paired timescales – June 2018" sections), the process should be started towards the beginning of accelerating activity (when RSAM is increasing) to increase the probability that evacuation is completed before PDCs descend. Contrary to the lay belief that hazards tend to be generated towards the end of a time window (Doyle et al. 2014), our analysis demonstrates that PDCs can develop at any point during paroxysm (Fig. 4). Deciding to evacuate only when PDCs descend can result in frustration (Panimaché Uno's unsuccessful evacuation on 3rd June 2018) or tragedy (Los Lotes' fate on the same day). On the other hand, evacuating earlier (i.e., when eruptive activity is accelerating) would undoubtedly cause some false alarms, in which people evacuate but PDCs are not generated or do not descend far down Fuego's barrancas. The possibility of false alarms or "crying wolf" is a known disincentive to future evacuation willingness (Dow and Cutter 1998). However, the alternative scenario of deciding to evacuate only once PDC generation is highly likely or certain will likely result in the situation we presently see at Fuego, where evacuation happens at the time of highest volcanic risk. We are not aware of any evacuations that have occurred at Fuego since 1999 which could truly be considered false alarms. It is unknown whether local or institutional actors would tolerate a certain number of false alarms (i.e., evacuations undertaken during increasing eruptive activity that may not generate PDCs) at Fuego in exchange for evacuating at a time of lower risk, and if so under what conditions would these false alarms be tolerable. Dialogue between these actors might generate more trust, and case studies at other volcanoes where trust exists between actors demonstrates that action can be taken while recognizing that the worst might not happen.

As well as forecasting uncertainty and difficulties in communication, situational barriers can inhibit timely response to crisis (Lazo et al. 2015). Situational barriers that disincentivize local people from evacuating at Fuego include limited resources, risk of loss of assets and livelihood, and communication failures (Naismith et al. 2020). The current evacuation policy at Fuego is an unusual example where the decision-makers are also the at-risk population and are expected to coordinate the evacuation decision using their own knowledge and resources. Although community-led evacuation has been successful at Fuego, particularly for Panimaché Uno, we note that this community has several resources that could advance their response timeline and that are not available to other communities ("Understanding the drivers and processes of community-led evacuations" section) – and that with these advantages, Panimaché Uno still experiences a response lag during evacuation. Other communities without Panimaché Uno's advantages are highly vulnerable to flow hazards during future crises, and community-led evacuation for these communities could perhaps be earlier with different contingent signals or with some dimensions of the process at Panimaché Uno incorporated. However, this examination should be tempered by considerations of their available resources, especially when compared to those of CONRED. An emerging situational motivator for evacuation is the apparent improving conditions in evacuation shelters – e.g., compare 13th September 2012 ("Paired timescales: September 2012" section) to 7th March 2022 (Bartel and Naismith 2023). Improving shelter conditions correspond to more people evacuating (~500 on 7th March 2022 vs. 1054 on 5th May 2023 (France24 2023)). Future research might study if improved shelter conditions encourage evacuation.

Calculating optimal response time during eruption is important at volcanoes where the at-risk population is dispersed widely over remote terrain (Marrero et al. 2013) or has limited points of egress in the evacuation zone (Wild et al. 2021). Our work on timescales (showing the variability of when PDCs descend, large forecasting uncertainties, different expectations of local and institutional actors of CONRED's involvement in warning dissemination and decision-making, and the high risk of evacuation routes that cross barrancas) shows just how complicated this calculation is at Fuego. Timescales of response vary greatly both between and within communities. However, work on constraining these timescales might provide valuable insights to actors in advance of a future eruptive crisis. For example, Sangre de Cristo is a particularly small rural village that repeatedly evacuated in paroxysms that produced PDCs (e.g., the eruption of 5th May 2017) (EFE 2017). Detailed analysis of Sangre de Cristo's previous evacuations could inform timescales for other communities to evacuate in future crises. Using Fig. 5 to work an evacuation backwards could be a useful exercise for local and official actors to undertake together, to constrain a community's particular required evacuation time and to address any community-specific needs. More time would be required for a larger community, and evacuation plans would have to consider barranca crossings and the effect of the rainy season (Fig. 8). This exercise, if involving actors from CONRED and INSIVUMEH as well as from the community, could provide a space for dialogue between multiple knowledges – an integration that is increasingly recognized as necessary for effective DRR (Mercer et al. 2012), and that has proven successful in other volcanic contexts (Mothes et al. 2015). With the tools above, a community could tailor their existing evacuation plan[3] to better suit their specific needs, resources, and location. We also emphasize that these conversations should actively involve the needs and priorities of women, who hold the burden for evacuation at Fuego (Bartel and Naismith 2023). Both warning messages and evacuation plans at Fuego should be highly specific given the heterogeneity of flow hazards and volcanic risk. CONRED and INSIVUMEH already understand this; however, implementation would likely require great financial and human resource. We hope our work highlights that different actors have different knowledges and resources available in a volcanic crisis, and that more dialogue between these actors might clarify areas where those knowledges and resources could be pooled for improved volcanic risk mitigation.

[3] CONRED already work with communities around Fuego to create tailored evacuation plans: each community should have a PLR (*Plan Local de Respuesta*) tailored to their needs.

Discussion – integrating scientific and local knowledge for future eruptive crises

Informed risk communication is vital to encourage protective action (Steelman and McCaffrey 2013). Communication of warning messages works best when the messenger understands the recipient's existing knowledge and beliefs about a hazard (Breakwell 2001). Conversely, failures in risk communication often happen when the messenger does not understand the recipient's perspective. Mental models can explain risk communication failures by identifying mismatches between lay and expert beliefs and by discovering lay perspectives that the expert has not imagined (Gibson et al. 2016). Our results show that officials are knowledgeable of the speed and dangers of PDCs, as are local people (("Understanding the drivers and processes of community-led evacuations: Warning dissemination" section). However, we still do not know mismatches between local and official knowledges at Fuego, and our results both here and in previous work suggest there are limited opportunities for exchange. Case studies we presented in "Discussion: Paired timescales" section (e.g., (Andreastuti et al. 2016)) showed that frequent communication between stakeholders and communities, and communication approaches that recognize the character of local communities (including previous experience of disaster), are effective at increasing local capacity at volcanoes where community preparedness is necessary. On page (18), we quote an official who expressed frustration when warning locals in Los Lotes who refused to evacuate. But did their message fall on deaf ears, or were those ears simply tuned to different priorities? We present Fig. 9 as a visualization of the different timescales over which actors around a volcano experience activity and acquire knowledge. This figure illustrates how these actors might have different experiences of the same volcano and knowledge of volcanic hazards and impacts occurring over different return periods. The pink wedge depicts the rich knowledge that local people possess through direct experience of volcanic activity on the timescale of a human lifetime. But

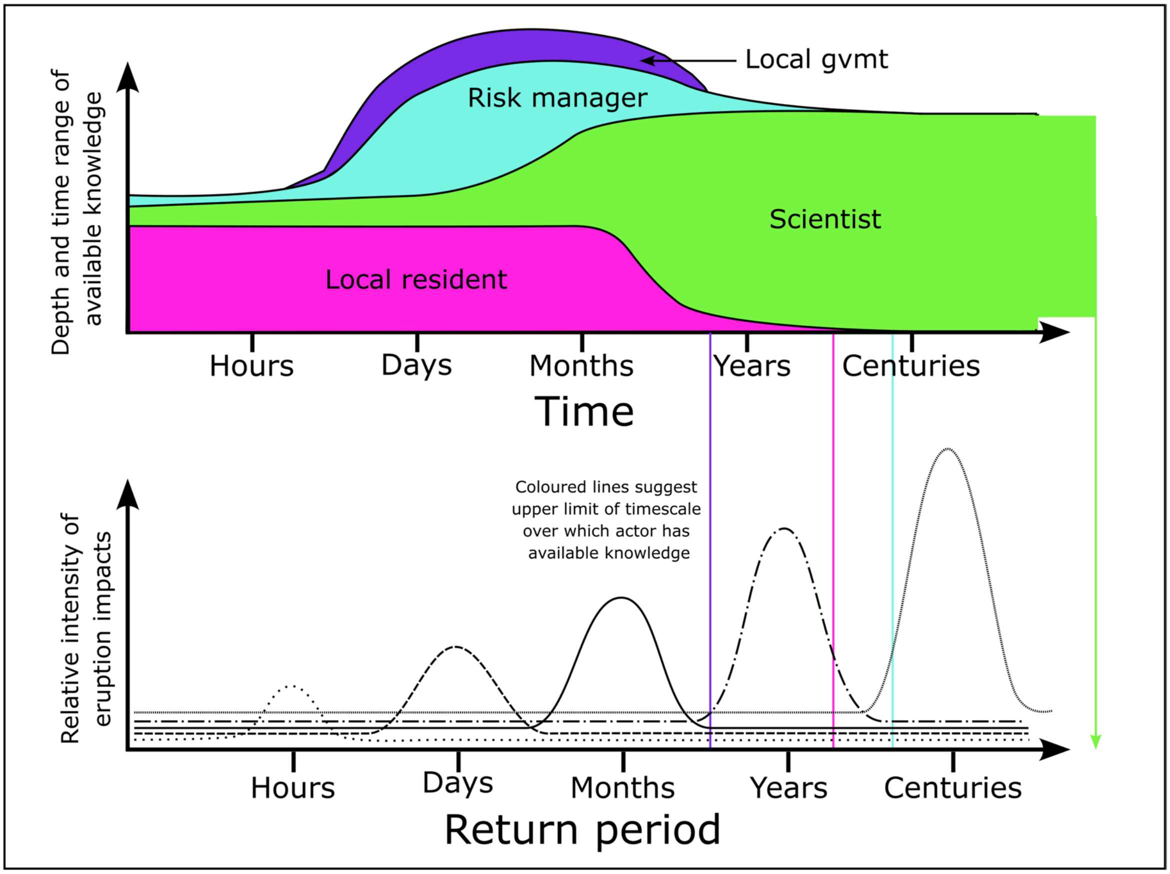

Fig. 9 Visualization of the depth and time range of different stakeholders' available knowledge about a volcano (top) and of relative intensity of eruption impacts and return period (bottom). Coloured lines suggest the upper time range of a stakeholder's available knowledge. For example, a scientist might have less available direct knowledge of a volcano than a local resident in the short term but can draw on more knowledge of a volcano over longer timescales through access to other information sources. This image can help us understand how different stakeholders might experience changes in volcanic activity in the context of their previous experience, available knowledge, and timescales over which this knowledge applies

what of future larger eruptions, that have no recent equivalent and thus lie beyond local people's experience? We believe this illustrates the value of collaboration with scientists beyond monitoring efforts. The green wedge shows how scientific knowledge relates to timescales greater than that of a human lifetime. This knowledge allows scientists to think about eruptions and impacts beyond the realm of historical experience. At Fuego and beyond, we see a need to bring into conversation these knowledges to create a shared understanding of risk. Such conversation would value the rich insights of experiential knowledge while acknowledging how scientific knowledge of the deeper past can help a community to prepare for the possibility of larger, more dangerous events. This exchange of knowledges could contribute towards 'healing the disjunct' highlighted by Barclay et al. (2019).

Informed risk communication is vital, but not sufficient, to ensure preventative action. Interviews in this paper show that local people do not quickly act as decision-makers during eruptive crisis at Fuego, instead waiting for CONRED's advice and presence. Situational barriers are major inhibitors to action in both decision models (e.g., PADM (Lindell and Perry 2012)) and in other studies at Fuego (Escobar Wolf 2013; Bartel and Naismith 2023). In particular, the possibility of encountering hazards on the evacuation route and the lack of adequate transportation within communities exposed to PDC hazard are two barriers that inhibit timely evacuation ((Bartel and Naismith 2023); this study). The "risk perception paradox" describes the situation where despite high awareness and direct previous experience of disaster, people often do not evacuate during crisis (Wachinger et al. 2013). This situation occurs at Fuego during volcanic crisis; we argue that the lack of evacuation is less a contradiction of peoples' experience and awareness than a combination of situational barriers to action, mismatches between local and official knowledges of volcanic hazard, and lack of opportunities for dialogue between local and official actors.

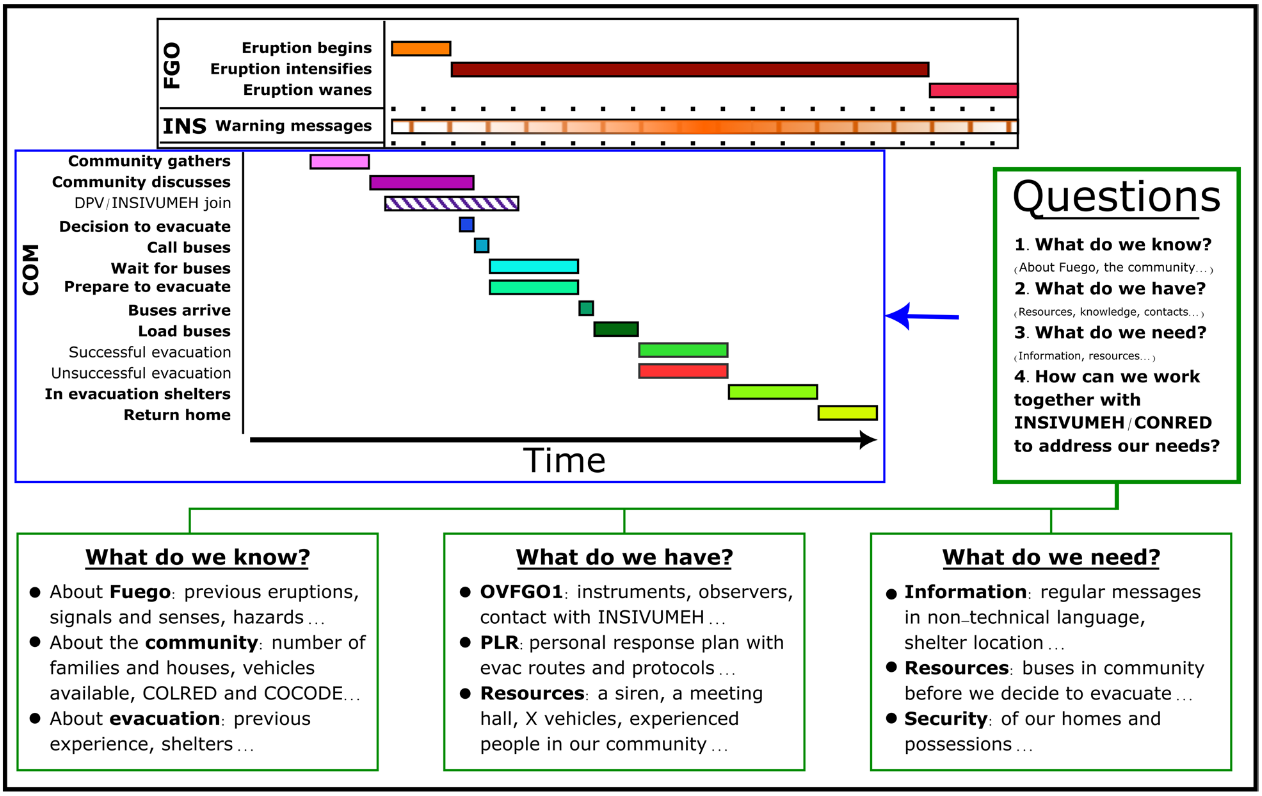

Fig. 10 Figure 5 adapted to visualize how local and official actors might exchange knowledges of volcanic hazards before a future volcanic crisis of Fuego. Upper green box contains questions about a community's knowledge and about its resources and needs during eruptive crisis, and a question to explore ways a community could work with INSIVUMEH and CONRED to identify and address gaps. Lower green boxes suggest answers for a specific community (here, Panimaché Uno). Blue box shows an idealized shift of community-led evacuation process to earlier in paroxysmal evolution, to decrease the risk of evacuating during climax and PDC descent

It would therefore be useful to consider how these actors might come together to exchange their knowledges in advance of future volcanic crises. These exchanges might facilitate communication between actors and contribute to timely evacuation. We present Fig. 10: a schematic adapted from Fig. 5 that visualizes how a community's evacuation process might be evaluated by local and official actors through asking questions on knowledge, resources, and needs (green boxes). The blue arrow illustrates how starting response earlier means that people are further through the evacuation process when hazards arrive, so that fewer people evacuate during eruptive climax. We present this figure as an opportunity to facilitate dialogue between actors to identify the community's specific needs.

In the "Discussion - paired timescales" section, we considered how local people's knowledge draws on historical experience and would be valuable in future eruptive crises comparable to those occurring at Fuego since 1999. However, Fuego has also produced larger eruptions that lie beyond historical experience. At other volcanoes where the scale of eruption has exceeded local people' experience, difficulties and even disasters have ensued (Barclay et al. 2019). Scientific enquiry can contribute knowledge through both study of larger prehistoric events and counterfactuals that expand the range of potential eruptive scenarios. This 'scientific imagination' – using science to explore beyond what can be observed in a human lifetime – is essential to consider future larger events and must be brought into dialogue with the people who live around a volcano to allow for meaningful preparation for such events. Establishing dialogue is particularly vital given that a successful response to a larger future crisis will demand more resources and swifter communication. Our figures aim to begin this dialogue by visualizing the different knowledges that actors hold over different timescales (Fig. 9) and by presenting a means by which these actors can exchange knowledges to build a shared understanding of resources and needs (Fig. 10). We see potential for future studies to support closer cooperation between local people, scientists, and risk managers through approaches that integrate their diverse knowledges over different timescales of a dynamic volcano.

Conclusions

Timelines are useful tools for tracing eruptive evolution and human response. We use paired timelines to investigate recent eruptions and evacuations at Volcán de Fuego, Guatemala. We find that paroxysmal climax and evacuations happen on similar time frames (~12 hours). However, we also find that response begins well after eruptive onset due to extended periods of warning and decision-making. In previous paroxysms, people have evacuated at eruptive climax when Fuego is most dangerous and evacuation routes are high risk. This "response lag" cannot be convincingly explained by local people having inadequate understanding of PDC hazard: instead, we suggest that the key drivers of this lag are the time needed for community visits, broken links in the communication chain, and a lack of agreed thresholds for shared decision-making. We also discuss how last-minute evacuation is associated with structural barriers and forecasting uncertainty. Evacuation currently requires 9–12 hours to complete. If in a future eruption a community decided to evacuate at eruption onset, evacuation could be completed before PDCs descend. However, if an evacuation were undertaken near eruptive climax, local people may face greater risk from flow hazards on the evacuation route than if they remain at home. We show that different actors have different tolerances for volcanic risk. We conclude by presenting a diagram that aims to acknowledge these differences by asking multiple stakeholders to identify their knowledge, needs and resources before an eruption, which might be useful to explore these differences in different volcanic contexts. Paired timelines might also be useful for this purpose. The aim of this paper is to contribute to understanding how people can "*convivir mejor*" ("live together better") with volcanoes in future eruptive crises that require local and institutional actors to work together for a coordinated response.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13617-023-00139-0.

Additional file 1. Graphic of coverage of MIROVA/SO_2/RSAM for 2016–2018 eruptions.

Additional file 2. Excel spreadsheet of timeseries values used for Fig. 2.

Additional file 3. Word document of INSIVUMEH bulletins used for timeseries construction.

Additional file 4. List of abbreviations used in this study.

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Authors' contributions

A.K.N. conducted, transcribed, and coded interviews, processed and analyzed timeseries data, created the timescales, and led the writing of the manuscript. J.P., J.B., and A.K.N. conceived the idea for this study during A.K.N.'s viva voce; all authors contributed to the study's further development in discussions. J.B. conceived the idea for Fig. 9. I.M.W. contributed to timeseries data analysis and produced Fig. 3. T.A. was instrumental in shaping and reviewing interview process and restructure of document. W.C. and G.C. contributed extensive information on the current evacuation process around Fuego including institutional roles. All authors reviewed the manuscript.

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Declarations

Ethics approval and consent to participate

This work was approved by the University of Bristol Research Ethics Committee (Project ID 5117) and consent was obtained from all study participants.

Consent for publication

All authors give their consent for this work to be published.

Competing interests

The authors have no competing interests to declare.

Author details

[1]School of Earth Sciences, Wills Memorial Building, University of Bristol, Bristol, UK. [2]School of Environmental Sciences, University of East Anglia (UEA), Norwich, UK. [3]Geography and the Lived Environment Institute, School of Geosciences, University of Edinburgh, Edinburgh, UK. [4]Departamento de Prevención en Volcanes (DPV) de la Secretaria Ejecutiva para la Coordinadora Nacional para la Reducción de Desastres (SE-CONRED), Antigua Guatemala, Guatemala. [5]Departamento de Vulcanología, Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología (INSIVUMEH), Guatemala City, Guatemala.

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