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Elaine T. Spiller

elaine.spiller@marquette.edu

Marquette University

Pablo Tierz

Geociencias Barcelona

Sylvain Charbonnier

University of South Florida

Eric C. P. Breard

University of Edinburgh

Rüdiger Escobar-Wolf

Michigan Technological University

Robert L. Wolpert

Duke University

Roberto Mérida

National Institute for Seismology, Vulcanology, Meteorology and Hydrology

Gustavo Chigna

National Institute for Seismology, Vulcanology, Meteorology and Hydrology

Eliza S. Calder

University of Edinburgh

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A comprehensive, multi-model exploration of flow
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Elaine T. Spiller^{1*†}, Pablo Tierz^{2,3†}, Sylvain Charbonnier⁴,
Eric C. P. Breard⁵, Rüdiger Escobar-Wolf⁶, Robert L. Wolpert⁷,
Roberto Mérida⁸, Gustavo Chigna⁸, Eliza S. Calder⁵

¹Department of Mathematical and Statistical Sciences, Marquette
University, Milwaukee, WI, USA.

²Geociencias Barcelona (GEO3BCN), CSIC, Barcelona, Spain.

³British Geological Survey, The Lyell Centre, Street, Edinburgh, United
Kingdom.

⁴School of Geosciences, University of South Florida, Tampa, FL, USA.

⁵School of Geosciences, University of Edinburgh, Edinburgh, United
Kingdom.

⁶Geological and Mining Engineering and Sciences, Michigan
Technological University, Houghton, MI, USA.

⁷Department of Statistical Science, Duke University, Durham, NC, USA.

⁸Instituto Nacional de Sismología, Vulcanología, Meteorología e
Hidrología (INSIVUMEH), Ciudad de Guatemala, Guatemala.

*Corresponding author(s). E-mail(s): elaine.spiller@marquette.edu;
ptierz@geo3bcn.csic.es;

Contributing authors: sylvain@usf.edu; eric.breard@ed.ac.uk;
rpescoba@mtu.edu; rlw@duke.edu; ermerida@insivumeh.gob.gt;
gachigna@insivumeh.gob.gt; eliza.calder@ed.ac.uk;

[†]These authors contributed equally to this work.

Abstract

Decisions that rely on assessments of pyroclastic density current (PDC) hazard for persistently active volcanoes that generate pyroclastic flows frequently can be particularly high-stake. As such, model-informed hazard assessments of PDCs must account for, and communicate, uncertainty in source conditions, topography, rheology and model structure. We present a systematic multi-model exploration of PDC scenarios at Fuego volcano, Guatemala, using TITAN2D and Volcflow. A Latin-hypercube design was used to generate 3600 simulations across six major barrancas (ravines), varying PDC volume (0.3–300 Mm³), flux-source duration and model-specific rheological parameters. We compare simulated cumulative inundation footprints, runouts, overbanking, flow depths and mobility metrics. Further, we identify scenarios that lead to inundation by using zero-censored Gaussian process emulators to resolve inundation thresholds at three locations in one specific barranca. The PDC models produce broadly comparable outer inundation envelopes and consistently identify the same topographic reaches as susceptible to overbanking, indicating that barranca geometry exerts the dominant first-order control on flow model pathways. Within these envelopes, however, their behaviour differs systematically. TITAN2D produces wider, generally shorter footprints and more extensive off-channel spreading, whereas Volcflow produces narrower, longer and more strongly channelised currents. These contrasts principally result from Volcflow’s constant retarding stress which makes mobility dependent on flow depth, while TITAN2D’s dominant Coulomb resistance does not. A new areal-ratio metric identifies a transition roughly around 10 Mm³ (in the two barrancas explored) at which TITAN2D currents over Fuego topography rapidly expand as thin overbanking sheets. Statistical emulator results show that source duration can influence inundation approximately 10 km from the summit and that model structure changes the relative susceptibility of on- and off-channel locations. These results establish a transferable framework for propagating source and model uncertainty into probabilistic PDC hazard assessment.

Keywords: Pyroclastic Density Currents, flow scenarios, volcanic hazard, TITAN2D, Volcflow, Fuego volcano

1 Introduction

Persistently active, pyroclastic density current-forming volcanoes around the world are killers ([Sapper and Termer 1930](#); [Jenkins et al. 2013](#); [Kasbani et al. 2019](#); [Andreastuti et al. 2019](#); [Charbonnier et al. 2023](#)) and we need to get better at understanding their hazard potential in advance in order to better mitigate disaster impacts. The work presented here is part of a package of work from the GCRF-funded Ixchel project that was developed in response to, and motivated by the 3rd June 2018 eruption disaster at Fuego volcano, Guatemala, where at least 430 ([CONRED 2019](#)) but possibly up to two thousand lives were lost when pyroclastic flows, extending almost 12 km from the summit, overbanked the ravine margins and overran the community of San Miguel Los Lotes ([Ferrés and Escobar-Wolf 2018](#); [Naismith et al. 2019](#); [Charbonnier et al. 2023](#))

We recognise that there are important and deeply-seated socio-political dimensions to such disasters, but these are largely beyond our capacity to tackle. Instead, as scientists working in the field of applied volcanology, we can contribute to reducing the impact of future disaster by ensuring that decisions – specifically those related to mitigating hazards from pyroclastic flows such as specific decisions around raising alerts, short-term evacuations or longer-term resettlement (Lavigne et al. 2017) – are made on the basis of, amongst other diverse types of information, the best possible available science.

The best science for situations like these means acquiring knowledge about the pyroclastic density current (PDC) generation and emplacement mechanisms, the temporal relationship of flow generation to other unrest or eruptive activity. The latter amounts to establishing a record, to the extent possible, of past PDC inundation footprints and frequency-magnitude relationships of recent or historical PDCs augmented by information related to PDCs from the volcano’s geological past. Combined with that information, the application of flow modeling to determine possible future areas of impact – using scenario-based or ideally probabilistic approaches and quantifying to the extent possible the uncertainty – is a measured and defensible scientific path forward. This knowledge, when fully integrated, can form the basis of a volcanic hazard map. Such maps around the world are instrumental at conveying the essence of the knowledge about the volcano to diverse users and audiences (Calder et al. 2015; Lindsay et al. 2023; Ogburn et al. 2023). In relation to PDC hazard specifically, and at volcanoes which produce PDCs relatively frequently, astute and timely evacuations of population from at-risk areas and/or implementation of longer-term resettlement programmes are the only effective means of mitigating loss of life impacts. The decision to advise evacuation, irrespective of who is responsible for such a decision, requires knowledge about the societal, logistical and geophysical situation, and included in the latter, specifically, an understanding of eruption patterns linked to PDC generation timings as well as PDC hazard zones.

Our research team comprises experts on field volcanology of Fuego, Fuego’s eruptive activity, flow modeling and probabilistic volcanic hazard assessment (PVHA). We bring together understanding of the eruption processes, field-based datasets, two geophysical flows models, statistics, and collective expert judgment needed to develop a methodology that forms part of the workflow towards a fully probabilistic hazard assessment for PDCs at Fuego.

Fuego represents an important example of a persistently-active, PDC-producing system, which yields relatively frequent small-to-moderate (2-7 km) runout flows in several active drainage systems around its relatively populated flanks (see Fig. 1). As such, there is a strong risk-based driver for undertaking a comprehensive analysis, and the availability of modestly good field data with which to constrain the modeling.

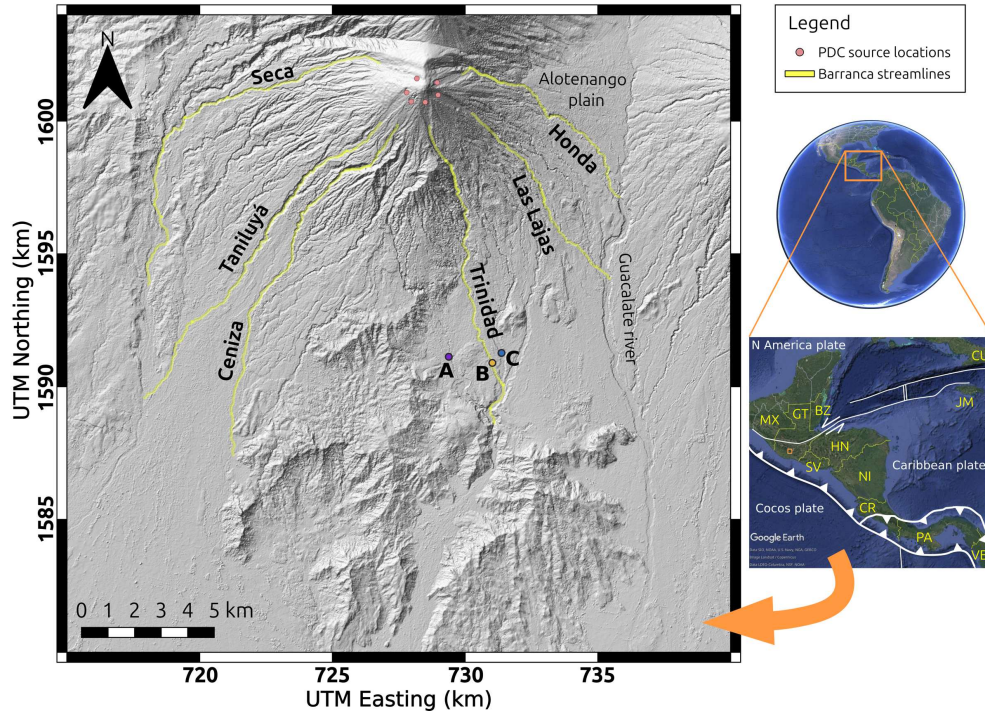


Fig. 1 Regional and local setting of Fuego volcano, a basaltic-andesitic stratovolcano situated in the Southern-Central volcanic cordillera of Guatemala. Subduction of the Cocos plate below the Caribbean plate is considered the main driver of magmatism related to Fuego's activity (right-hand side insets). Regional tectonic setting adapted from [Gazel et al. \(2021\)](#).

Our goal in this work is to develop a systematic flow modeling and statistical emulation framework that can support a future probabilistic assessment of PDC inundation at Fuego. We use two widely applied depth-averaged flow models, TITAN2D [Patra et al. \(2005\)](#) and Volcflow [Kelfoun and Druitt \(2005\)](#), which employ contrasting rheological formulations and use different approaches in their respective numerical implementations. The two-model strategy is not intended to identify a single preferred model. Rather, it allows us to examine epistemic uncertainty associated with model structure and rheological formulation, and to determine which hazard-relevant predictions are not model-choice dependent. This work therefore builds on our previous work on the use of statistical emulators for probabilistic PDC hazard assessment ([Bayarri et al. 2009](#); [Spiller et al. 2014](#); [Bayarri et al. 2015](#); [Rutarindwa et al. 2019](#); [Spiller et al. 2020](#); [Tierz et al. 2024](#)) by using and comparing two models, designing a different strategy to sample the relevant PDCs at Fuego based on the different flow model rheological formulations, and also by undertaking sets of drainage-specific simulations. For this work, we carry out 3600 simulations, comprising 300 simulations with each model, for each of six major barrancas (locally used term for deeply incised ravines) draining the volcano. PDC volume, flux-source duration and model-specific

rheological parameters are varied using a space-filling experimental design. The resulting ensemble represents a systematic exploration of scenario space rather than a probability-weighted sample. We compare cumulative inundation envelopes, maximum runout, channelisation, lateral spreading, overbanking and flow distal thinning characteristics. We further distinguish throughout between the rheological formulations of the model inputs and mobility or impact metrics derived from the simulated outputs. The resulting catalogue of inundation footprints, maximum runouts, overbanking extents and grid-point-specific maximum flow depths is designed so that subsequently probability models for PDC source conditions and model parameters can be propagated through it.

This work makes five principal contributions. First, building on previous model comparisons (e.g. Charbonnier and Gertisser 2012; Ogburn and Calder 2017), it provides the most comprehensive systematic comparison of TITAN2D and Volcflow to date, demonstrating how their differing rheological formulations and numerical implementations influence runout, channelisation, lateral flow spreading and overbanking. Second, it develops a systematic and transferable framework for applying numerical flow models at frequently active, PDC-producing, volcanoes. Third, it evaluates the extent to which overbanking locations and inundation patterns are independent of model choice, thereby distinguishing topographic controls from model-dependent behaviour. Fourth, it examines the limitations for simulated flows of conventional scalar mobility metrics, and introduces a new areal-ratio metric to characterise the nature of distal thinning within inundation footprints. Finally, we use statistical emulators of PDC simulations to identify the combinations of volume, duration and rheological conditions that separate inundating from non-inundating scenarios at selected locations around Fuego.

In Section 2 we introduce the models and rationale for developing the combined approach devised here. In Section 3 we summarize current knowledge about PDCs at Fuego and describe the data available for constraining our modeling. In Section 4 we describe our methods, including our use of simulation output data to compute and analyze our results. In Section 5 we provide our findings, illustrating them specifically for two barrancas (ravines) of particular interest, due to their topographic configuration and potential risk implications. Finally, in Section 6 we discuss how our findings complement previous work in relation to the application of TITAN2D and Volcflow as well as implications for understanding PDC behaviour and emplacement at Fuego. We also place the work in its broader context as part of a workflow which will be *scaled up* to support a full PVHA of PDCs at Fuego volcano in order to develop a new operational and fully probabilistic hazard map.

2 Pyroclastic density current models for hazard analysis

Since the emergence of computational volcanology in the 1980s and 1990s, a range of approaches have been developed to simulate PDC runout, inundation area, flow

231 depth, velocity, and related impact metrics, from simple empirical tools to fully three-
 232 dimensional multiphase solvers (e.g. [Dufek 2016](#); [Lube et al. 2020](#); [Tierz et al. 2021](#);
 233 [Charbonnier et al. 2025](#)). Depth-averaged models provide intermediate-complexity
 234 solutions that are particularly well suited to scenario-based, as well as probabilistic
 235 PDC hazard analysis. They solve depth-averaged mass and momentum equations
 236 over digital elevation models, allowing the simulated flow to interact with realistic
 237 topography while remaining computationally efficient enough for systematic explo-
 238 ration of uncertainty in source volume, duration, location, and rheological parameters.
 239 Likewise, limitations of depth-averaged models are well recognized. They collapse the
 240 vertical structure of the current into depth-averaged quantities and therefore cannot
 241 resolve vertical stratification, turbulent entrainment, settling, elutriation, pore-
 242 pressure feedback, or dilute-concentrated layer coupling except through simplified
 243 parameterizations. Nevertheless, for dense, granular-flow PDCs, they occupy a useful
 244 “intermediate-complexity” space – sufficiently physical to respond to topography and
 245 changing source conditions, yet sufficiently efficient and robust to facilitate ensemble
 246 modeling approaches (e.g., [Esposti Ongaro et al. 2020](#); [Gueugneau et al. 2021](#)).
 247
 248 In this work, we employ two widely used depth-averaged PDC models, TITAN2D
 249 and Volcflow, to explore potential scenarios of PDC runout, inundation footprint,
 250 and maximum flow depth at Fuego volcano. TITAN2D was developed for geophysical
 251 mass flows over natural terrain and solves shallow granular-flow equations using
 252 a finite-volume, adaptive-mesh framework ([Pitman et al. 2003](#); [Patra et al. 2005](#)).
 253 In most PDC applications, TITAN2D has commonly been used with Coulomb-
 254 or Voellmy–Salm-type basal resistance formulations, in which mobility is governed
 255 either by frictional terms only (Coulomb) or, where included, frictional and velocity-
 256 dependent dissipation terms (Voellmy–Salm) ([Voellmy 1955](#); [Salm et al. 1990](#); [Savage
 257 and Hutter 1989](#)). In the configuration used here, we employ the Voellmy–Salm
 258 formulation, which includes a dry Coulomb friction type parameter and a velocity
 259 dissipation parameter, but explore the dominant influence of the Coulomb-friction
 260 parameter while keeping the additional dissipation parameter fixed, so that the
 261 model ensemble remains tractable and interpretable. TITAN2D has been applied to a
 262 range of volcanic mass-flow problems and has become a standard reference model for
 263 investigating how source volume, source geometry, basal resistance, and topographic
 264 confinement influence inundation patterns (e.g. [Spiller et al. 2014](#); [Patra et al. 2020](#);
 265 [Gueugneau et al. 2021](#)).
 266
 267 Volcflow, also a depth-averaged model, differs from TITAN2D in its numerical imple-
 268 mentation and in the rheological formulation adopted here ([Kelfoun and Druitt 2005](#);
 269 [Kelfoun et al. 2009](#)). In particular, Volcflow has been widely used with a constant
 270 retarding stress rheology for dense volcanic granular flows (e.g. [Charbonnier and
 271 Gertisser 2012](#); [Ogburn and Calder 2017](#); [Gueugneau et al. 2009](#); [Charbonnier et al.
 272 2020](#)). This formulation represents flow resistance through a characteristic basal stress
 273 rather than through a dimensionless friction coefficient. Previous applications have
 274 shown that such a formulation can reproduce important aspects of dense PDC and
 275 volcanic mass-flow emplacement, including channelized propagation and deposition
 276

(Kelfoun et al. 2009). In this work, the Volcflow ensemble is parameterized using the constant retarding stress with an additional fixed turbulent dissipation parameter, providing a useful contrast with the TITAN2D ensemble in which mobility is primarily controlled by a frictional coefficient.

Using TITAN2D and Volcflow together is not intended to identify a single “best” model. Rather, the two-model design allows us to sample a broader space of plausible model behaviors and in order to expose epistemic uncertainty associated with model structure and rheological formulation. This is important because model parameters such as TITAN2D friction or Volcflow constant retarding stress are not directly observable. Instead, they are inputs that control simulated mobility. By contrast, quantities such as maximum runout, inundation area, overbanking location, maximum flow depth, and depth-threshold exceedance are simulation outputs that can be compared across models and, importantly, where possible, against field constraints. The relationships determined between rheological input parameters and simulated mobility or impact metrics are central to how the workflow here was subsequently developed (see below).

3 Pyroclastic density currents at Fuego volcano

Fuego and its persistent activity. Fuego is a high (~ 3800 m a.s.l.) and steep stratocone, that is bounded immediately to the north by the adjacent Acatenango cone and altiplano, and to the south its flanks extend around 25 km to the coastal plain. Since the start of the current cycle of activity in 1999, Fuego has exhibited a high level of persistent or background activity that usually involves small explosive eruptions from the summit crater occurring several times per day to several times per hour. During some periods of time, this background activity has also involved the eruption of lava flows, occurring over durations spanning a few days to months. Background activity at Fuego can also be interrupted by phases, usually lasting 1-3 days, of more intense higher magnitude explosive activity termed paroxysms (e.g., Lyons et al. 2010; Escobar Wolf 2013; Aldeghi et al. 2019; Naismith et al. 2019). Our team has now identified 86 such paroxysmal eruptions since the start of the current activity cycle in May 1999.

Paroxysms usually involve continuous explosive activity, often generating pulsating lava fountains, the development of an eruptive column extending hundreds of meters to a few kilometers above the crater, the dispersion of a tephra cloud over a distance of tens to hundreds of kilometers, and sometimes also the formation of lava flows extending a few kilometers in length for the duration of the paroxysm. Many paroxysms also produce PDCs. These range from relatively small flows extending 1 or 2 km down the upper slopes of the stratocone, to more voluminous PDCs extending to 7 km or more (Lyons et al. 2010; Escobar Wolf 2013; Naismith et al. 2019; Charbonnier et al. 2023). It is these larger PDCs that extend into the mid-flank region

of the stratocone – especially on the east, west and southern flanks – that threaten communities, transportation and evacuation routes, and agricultural land.

PDCs generation mechanisms at Fuego. PDCs at Fuego are likely generated by a variety of mechanisms but a common mechanism observed in recent decades is the collapse of metastable, or oversteepened, volcanoclastic material (Escobar Wolf 2013). This involves the collapse of pyroclastic material and lava flow piles that have accumulated during the persistent explosive activity around the crater as well as in areas forming the heads of the six main barrancas radiating from the summit (Escobar Wolf 2013; Aldeghi et al. 2019; Risica et al. 2022; Charbonnier et al. 2023). This, usually hot, PDC source material is heterogeneous in nature but is dominated by dense bombs and spatter as well as finer tephra. Previous work has established a range in emplacement temperatures (e.g., Risica et al. 2022), and along with unpublished work by the authors, we infer that these collapses typically involve freshly erupted material as well material accumulated over the previous weeks-months-years.

The oversteepened material collapse mechanism is likely complex, and influenced by the specific make-up and structural configuration of the pile. The collapses also predominantly occur as retrogressive failures over time, typically covering many hours (Charbonnier et al. 2023). Although detailed modeling of the specifics of complex pile collapse processes is beyond the scope of this work, the simplified PDC source and initiation conditions for our simulations are directly motivated by the generic collapse pile model described above (Sec 4.).

The flank material collapse as the source process for PDCs at Fuego volcano is consistent with observations of many of the PDCs deposits from both recently observed and older (historic and prehistoric) PDCs (e.g., Escobar Wolf 2013; Risica et al. 2022; Charbonnier et al. 2023). Such deposits can broadly be classified as block and ash deposits, with larger quite dense clasts (blocks and bombs) embedded in a relatively coarse ash matrix. Although uncommon, there are also scoria-rich PDC deposits in Fuego’s geologic record (Escobar Wolf 2013), which may reflect the occurrence of column collapse PDC generation mechanisms in the past. The generation mechanism of such flows would be less well captured by the simplified source mechanism considered in our models. Flow propagation and run out of such column collapse PDCs might be somewhat different from the flows modeled in our work, although the extent of those differences is not clear. This is one caveat to keep in mind when analyzing the outputs of our models.

PDC occurrence at Fuego. From the 86 paroxysms identified since 1999, 31 have produced PDCs with runout distances above 3.2 km, large enough to produce deposits that have been mapped using satellite and/or field observations. An additional number of paroxysms have produced PDCs of smaller size which were limited to the upper flanks of the edifice and have not been mapped. PDCs have also been documented during previous episodes of activity, (Bonis and Salazar 1973; Davies et al. 1978; Rose et al. 2008, e.g., 1971, 1973 and 1974). Many other eruptions during

the 1940's to 1970's activity cycle, as well as other historical eruptions (e.g. 1932, 1880, 1717, 1581-82, etc.) have, based on eye witness descriptions, also produced PDCs. Radiocarbon ages for historic and prehistoric PDC deposits also show their recurrence over the past centuries and millennia (Escobar Wolf 2013). Such PDC deposits are not only abundant (more than 10 units in some sections), but individual thicknesses can exceed 20 m illustrating that generation and deposition of large PDCs on Fuego's mid to lower flanks over the previous centuries has been common. As such, the complete list of eruptions producing PDCs during the whole of the historical period is likely significantly longer than those documented since 1999. This makes Fuego, on a global scale, one of the most frequent producers of PDCs, with some of those PDCs reaching relatively large volumes ($> 10^7 \text{ m}^3$), and long runouts ($> 12 \text{ km}$) as was the case of the 3 June 2018 flow.

We focus our attention here on six of the currently most active *barrancas* (ravines) on Fuego, although we note that there are many more that could have been active in the past, or that could become active in the future. Some of these barrancas branch into more than one channel in their downstream sections, e.g. Las Lajas and El Jute illustrating the complexity of the drainage system arrangement around the volcano (see Fig. 1 central inset). These barrancas act as the main pathways to channel both PDCs and, much more frequently, lahars to the lower flanks of the edifice. For each of these six barrancas we identify six corresponding PDC source locations (See the location of the orange dots on Fig. 1 and Table 1) that are then used for initiating the simulations (see Section 4).

Due to the relatively high levels of exposed population on the southern flanks of Fuego, there are many locations in this area for which site-specific hazard or risk assessment could be usefully undertaken. In this work, we identify three points of interest A, B and C that represent specific, small centres of population, in and around the medial to distal reaches of Barranca Trinidad ($\sim 10 \text{ km}$ away from the summit). We use these locations here to illustrate some of our analyses and main results, and will develop this further in future work that will provide a statistically robust analysis of the hazard at those locations along with discussion related to the implication of those results for these and other locations around the flanks of the volcano. It is important to note that by considering these three locations, we do not indicate that they are more or less important than a multitude of other locations of interest on the southern flanks. We do however, stress they are real locations where people live and for which the knowledge that comes from both this and forthcoming work has serious implications and potential consequences. We undertake this work with awareness of the complexity involved in the wider disaster risk reduction landscape in Guatemala and its short and long-term impacts many of which are highly problematic (Ferrés and Escobar-Wolf 2018; Naismith et al. 2020; Cabrera Pacheco et al. 2024; Calder et al. 2025), but with the belief that improvements to the overall system will also come with the contribution of more robust science.

Fuego Volcano			
Barranca name	UTM Easting (m)	UTM Northing (m)	PDC count
Seca	728179	1601600	8
Taniluyá	727797	1601074	3
Ceniza	727968	1600732	13
Trinidad	728497	1600711	7
Las Lajas	728981	1600981	21
Honda	728949	1601451	2

Table 1 Summary information for each of the six main active Barrancas at Fuego volcano including UTM coordinates of the head of each barranca which represent the source area used for PDC simulations (see Fig. 1), as well as the number of recorded PDCs that descended each of those barranca between 1999 and 4 May 2023.

4 Simulation data and methods

We explore two of the most-widely used PDC models, TITAN2D (v.4.2.0) and Vol-flow (one phase), to inform potential scenarios of PDC runout, inundation footprints, and flow depths at and around Fuego volcano.

Digital terrain of Fuego volcano. These models require a digital representation of the terrain, ideally in the form of a digital terrain model (DTM) which describes the forms of the bare terrain surface, although often a digital surface model (DSM) is used instead, which represents the topmost surface above the terrain, including vegetation canopy, building roofs, etc. In our case, we used an 8 m resolution (pixel size) DSM resampled from the 5 m resolution commercially available ALOS AW3D DSM, generated from optical imagery captured by the PRISM instrument aboard the JAXA ALOS satellite between 2006 and 2011. The DSM therefore represents the terrain, including the tree canopy, as it was captured in the images sometime between 2006 and 2011, or a blend of conditions between those dates. Although some of the finer details, particularly within barranca channels, have changed since then, we believe that most of the terrain conditions are reasonably close to current conditions otherwise.

Initializing simulations. We aim to model PDCs generated from the collapse of metastable, hot volcanic material that accumulates in the proximity of the crater (Fig. 1, see Section 3). We want to be able to route given volume of flows into given barrancas so as to allow for comparison with the mapped natural PDC volumes as determined for individual barrancas. Ultimately, our goal is not to reproduce source process in our simulations, but rather to reproduce the flow behavior as it propagates downslope. Thus, we undertake the PDC modeling on a barranca-by-barranca basis. We select PDC initiation points roughly 0.5 km down from the craters edge, located at the head of each barranca (Fig. 1). The choice of 0.5 km strikes a balance between ensuring that the bulk of the material flows into the barranca of interest, while also ensuring that the source is relatively near the summit so as to be consistent with zero initial velocity in the downflow direction. PDCs with simulated sources located closer

to the summit spread into several barrancas, simultaneously. Our simulation-source locations are an area covered by an ellipse of $150 \text{ m} \times 50 \text{ m}$, major and minor semi-axes, respectively, oriented parallel to the main strike of the head of the barranca. We report the center and orientation of those source location ellipses in Table 1.

To define the PDC volume used in each simulation, we use flux sources of different durations and, hence, average flux rates. These flux rates are expressed as influx per unit area in TITAN2D (Patel et al. 2022; Tierz et al. 2024), and are related to simulated PDC volume as follows,

$$V = \frac{\dot{h} d \pi a b}{4}, \quad (1)$$

where V is PDC volume (in m^3), $\dot{h}$ is maximum initial influx per unit area (in m/s), d is flux duration (in seconds) and a , b are the major and minor semi-axes of the ellipse (both axes in m) acting as the PDC source. Note, flux sources in our Volcflow simulations are set up to replicate the behavior of flux sources in our TITAN2D simulations. The choice of an ellipse (elongated in the direction of the strike of the drainage of interest), instead of a circular flux source, is motivated by attempting to keep the PDC source area within the limits of the barranca-head lateral walls, while still maximizing the total basal area of the flux source (e.g. πr^2 vs $\pi a b$). This is particularly important for large PDC volumes with shorter durations, in spite of the fact that the use of a flux source, instead of a pile source, already works in favor of limiting this issue (see Section 2).

Design of simulation suites. Our goal in this work is to explore PDC inundation under a wide range of scenarios that will allow us, eventually, to posit various probability density function (pdf) models of aleatory variability for scenarios and utilize this suite of simulations for PVHA studies and uncertainty quantification. That is, we are not presupposing a single aleatory pdf and sampling from that pdf to initialize PDC simulations. Instead, we consider a space-filling design of scenarios that spreads simulation inputs over wide ranges of scenario/input space. We choose to vary three input parameters: PDC volume (V), the duration of the PDC flux initialization (d), and a rheological parameter – constant retarding stress (CRS) for Volcflow and Coulomb-friction (μ) for TITAN2D. As mentioned in section 2, the Voellmy-Salm rheology modeled with TITAN2D includes both a Coulomb friction and turbulent dissipation coefficient. We also explored the effects of varying the turbulent dissipation coefficient on PDC mobility, but concluded that the Coulomb-friction is by far the dominant rheological parameter controlling simulated mobility. For all three input parameters, a space-filling design was chosen by Latin hypercube sampling (LHS) (Johnson et al. 1990) on a logarithmic scale over the respective range of each parameter. Focusing first on PDC volume, we consider volumes sampled between 0.3 Mm^3 and 300 Mm^3 . It is worth emphasizing that the sampled simulations in the design are not assigned probabilities. Instead, this wide range of volumes (up to very large volumes!) is informed by an elicitation (see S.1 of the Supplementary Materials for details) and chosen in order to cover the range of plausible volumes well into their

pdfs tails. In other words, this design explores potential large-volume tail scenarios in addition to those of small-to-medium volume events on the scale of those that have occurred at Fuego since 1999.

For both Volcflow and TITAN2D, a volume and a flux duration together determine the average volumetric flux rate specified to initialize a simulation. Note that the average (over space and time) volumetric flux rate within simulations refers to the rate at which the volume of material becomes available to flow (see [Patel et al. 2022](#), for details), not an actual volumetric flux of flowing mass, with velocity and momentum. The average volumetric flux rate is just a convenient, heuristic modeling mechanism to handle the inclusion of volume and mass into the flow, distributed over time, at rates that we can control. To tie simulated PDC volumes to the flux-source durations, we build on evidence that higher-volume flows are expected to be associated with longer durations (e.g. [Roche et al. 2021, 2024](#)), and construct a simple model (linear on a log – log scale) that links PDC volume and flux-source duration. This allows us to explore the effects of duration (average volumetric flux rate) for a given volume. For the smallest volumes under consideration, duration rates are taken in the range of 16.5-46.5 seconds (6800-19200 m³/s), and up to 330-660 seconds (0.50-0.95 Mm³/s) for the largest volumes. (See expert elicitation in [S.1](#).) The linear model defining the minimum of the duration window as a function of volume is

$$\log_{10}(d) = 0.435 \log_{10}(V) - 1.17, \quad (2)$$

and the curve defining the maximum of the duration window as a function of volume is

$$\log_{10}(d) = 0.383 \log_{10}(V) - 0.44. \quad (3)$$

Through many dozens of exploratory simulations, we found that these duration ranges (and corresponding average flux rates) for moderate-volume flows (e.g. $V < 5\text{-}10 \text{ Mm}^3$) do not typically lead to extensive PDC overbanking in very proximal areas, which is consistent with our modeling set-up objectives. We then use the curves defined in Equations 2-3 as lower-duration and upper-duration bounds within which we chose a space-filling design for both TITAN2D (Fig. 2a) and Volcflow (Fig. 2a). Both designs have $N = 300$ simulations each selected to sit within the lower-duration and upper-duration curves.

Each simulation design point is a triplet, (volume, duration, rheological parameter), requiring a value of the rheological parameter in addition to volume and duration values. For Volcflow, the rheology parameter is CRS varying from 3000-12000 Pa. In the $CRS - V$ plane, these LHS design point projections appear uniform (Fig. 2d). The relationship between Coulomb-friction and volume follows a decreasing trend in friction as volume increases ([Ogburn 2008](#); [Ogburn et al. 2016](#)). We employ the “hockey stick” trend from ([Rutarindwa et al. 2019](#)), which bounds friction from below at small values and assumes a linear trend on the log-log scale that ends prior to 50 Mm³ where the decreasing trend and the lower bound meet. The resulting design is shown in Fig. 2b, and details of the particular trend chosen for this design

are described in S.2 of the Supplementary Materials. Fig 3 shows the output of four simulations, two TITAN2D simulations with identical scenarios, one for each of barrancas Trinidad and Honda, and two Volcflow simulations with identical scenarios one for each of the same two barrancas.

Leveraging PDC simulations with Gaussian Process emulators. We can glean many interesting results directly from this comprehensive set of simulations through standard mobility metrics (L , A , H/L , $A/V^{2/3}$) as determined for the simulated flows. Yet physics-based simulators like TITAN2D and Volcflow are challenging to use in PHVA as they are computationally expensive to exercise for a single scenario, let alone the 10^3 - 10^6 necessary for Monte Carlo (MC) simulations. Statistical surrogates are now a common approach to ease this computational burden and aid in sensitivity analysis, MC simulations, and uncertainty quantification for expensive partial differential equation-based simulators (Smith 2024; Berger and Smith 2019). Statistical surrogates or *emulators* model a quantity of interest (QOI) from a simulator (e.g., maximum PDC flow depth at a single location using a given flow model) as a random function Bayarri et al. (2009); Spiller et al. (2014); Rutarindwa et al. (2019); Tierz et al. (2024). Gaussian process (GP) emulators employ a Gaussian stochastic process as that random function model Sacks et al. (1989b,a); Currin et al. (1988) that is characterized at each input scenario by its predictive mean and predictive variance. One advantage of GP emulators is that their predictive mean offers an approximation of the output QOI at untested inputs (e.g., at a volume-duration-rheology scenario not in the $N = 300$ training design). Additionally, they offer uncertainty estimates for using the emulator in place of the simulator through the GP variance. Further, for deterministic simulators, the GP emulator predictive mean acts as an interpolator of the training data. Once a GP emulator is fit, evaluations of its predictive mean at untested input scenarios are computationally “free” (a fraction of a second on a laptop).

The design of PDC simulation scenarios plotted in Fig. 2 is well suited to training GP emulators. To demonstrate this, we consider PDC simulations in a single, barranca (e.g., Trinidad) and a QOI as the maximum simulated flow depth at a specific location (e.g., point A from Fig. 1). This input-design/output-QOI training set is then used to fit a GP emulator which models the input/output relationship of a simulator, i.e. the flow model. The work involved in “fitting” a GP emulator rests primarily on determining the GP’s correlation length scale in each input dimension, details of which can be found in (Santner et al. 2018; Gramacy 2020). One drawback of using GP emulators of PDC simulators is that the simulator output QOI (here, max flow depth) is necessarily either positive or zero, while Gaussian processes can take on any value, including negative values. Further, typical GP emulators make an assumption of stationarity. Fitting a GP to output data that is flat (zeros) in some regions of scenario space and which increases (with volume) in others violates the stationarity assumption. Instead, to investigate the nuanced behavior of the two PDC simulators at our points of interest near barranca Trinidad, we will employ the zero-censored GP

emulator, or zGP Spiller et al. (2023); Tierz et al. (2024). The zGP relies on a pre-processing step that imputes negative output values for the (true) zero-output data that are consistent with a GP fit only to the positive-output data. Then, a Gaussian process is fit to this augmented zGP data set (positive output and imputed-negative output). The predictive mean of the zGP evaluated at an untested scenario is then the identity (if the zGP prediction is positive), or zero (if the zGP prediction is negative).

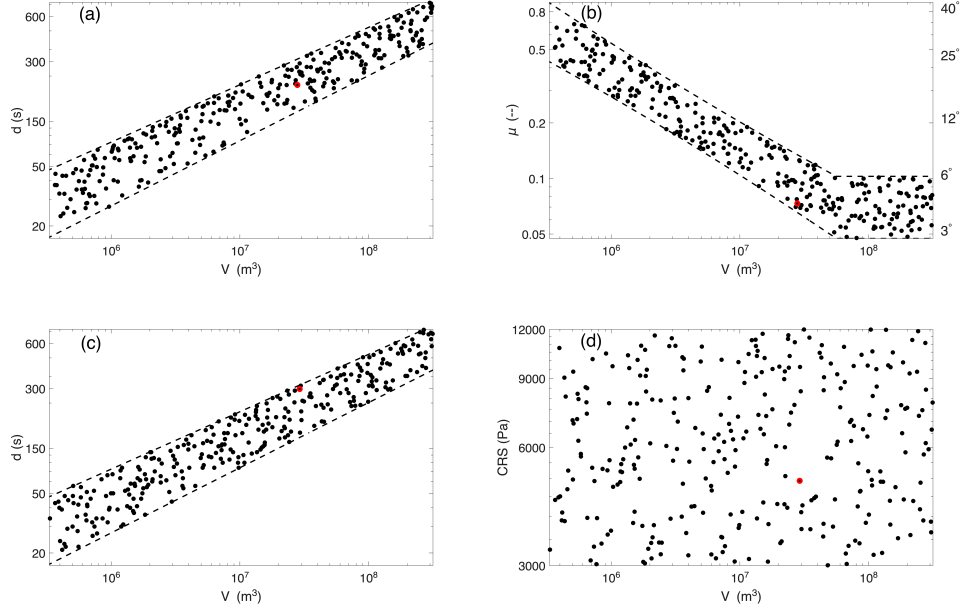


Fig. 2 Design of PDC simulations at Fuego volcano that vary over volume duration, and rheology parameters for each simulation of TITAN2D (top row) and Volcflow (bottom row). All axis labels are on a logarithmic scale. For TITAN2D, each simulation corresponds to one of the (volume, duration, Coulomb-type friction) triplets plotted pair-wise as a) duration vs volume, and b) Coulomb-friction, μ , vs volume. (Note, $\theta^\circ = \arctan(H/L)$ is indicated on the right vertical axis, for reference.) For Volcflow, each simulation corresponds to one of the (volume, duration, constant retarding stress) triplets plotted pair-wise as c) duration vs volume, and d) constant retarding stress vs volume. The red-circled simulation in a-b corresponds to the TITAN2D simulation design triplet ($V = 27.97 \text{ Mm}^3$, $d = 174.4 \text{ s}$, $\mu = 0.0732$) whose output is plotted in Fig 3a-b for barrancas Trinidad and Honda, respectively. The red-circled simulation in c-d corresponds to the Volcflow simulation design triplet ($V = 26.61 \text{ Mm}^3$, $d = 248.0 \text{ s}$, $CRS = 4.932 \text{ kPa}$) whose output is plotted in Fig 3c-d for barrancas Trinidad and Honda, respectively.

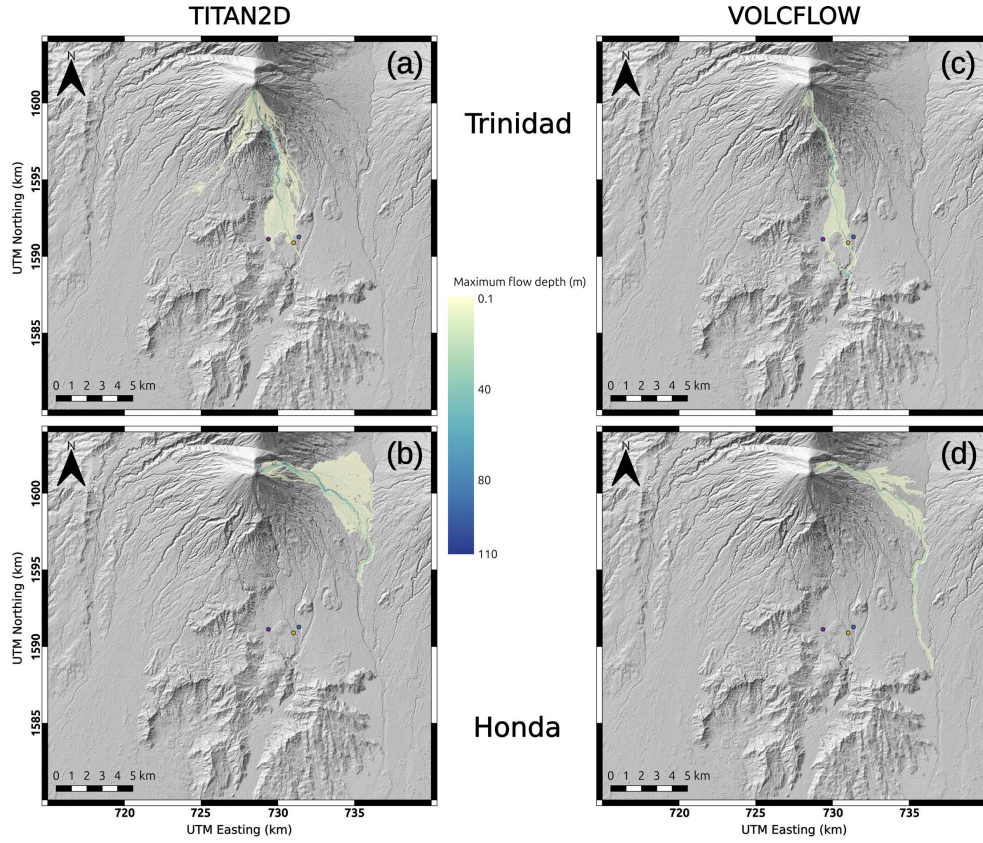


Fig. 3 Examples of PDC simulations at Fuego volcano for the two PDC models explored (TITAN2D, a-b; and Volcflow, c-d) and two barrancas of interest (Trinidad, a, c; and Honda, b, d). The simulated flows are relatively large in volume ($V \sim 30 \text{ Mm}^3$) but not close to the largest simulated in this work. Design parameters (common across barrancas for a given PDC model) are for TITAN2D: $V = 27.97 \text{ Mm}^3$, $d = 174.4 \text{ s}$, $\mu = 0.0732$; and for Volcflow: $V = 29.16 \text{ Mm}^3$, $d = 248.0 \text{ s}$, $CRS = 4.932 \text{ kPa}$, where V is PDC volume, d is flux-source duration, μ is Coulomb-type friction parameter, and CRS is Constant Retarding Stress. (For reference, these design points are highlighted in Figures 2, 9). NB. Points of interest A, B and C from Figure 1 are displayed in the same colors, but not labeled, in order to help with clear visualization of PDC footprints.

5 Results

Based on the comprehensive collection of PDC footprints obtained from running the two PDC models at each of the design points chosen ($N=300$ TITAN2D and $N=300$ Volcflow simulations for each of the six barrancas), we first calculate the cumulative spatial extent of these footprints, as the number of simulations whose PDCs reach different grid points on and around Fuego. For elucidation purposes, we focus the presentation of results on barrancas Trinidad and Honda, but results for other barrancas are presented in S.3 in the Supplemental Materials. For barrancas Trinidad

and Honda, see Fig. 4, and for other barrancas, see Fig. S4. At first order the outer envelopes of these cumulative footprints are not very different across the two PDC models in the same barranca. Generally though, TITAN2D PDC footprints are wider but shorter (i.e. shorter maximum runouts) compared to Volcflow footprints, which are narrower cross-barranca but display longer maximum runouts. For the largest volume flows, Volcflow simulations have maximum runouts of approximately 4 km (Trinidad) and 5 km (Honda) longer than the same volume flows simulated by TITAN2D (Fig. 4). This may be expected since the terrain slope at which the constant retarding stress model (Volcflow) starts to decelerate depends on the thickness of the flow. That is, the flow in confined channels or valleys may remain “thick” and therefore progress further than the flow of the frictional model (TITAN2D). In TITAN2D, the terrain slope at which the flow starts to decelerate is only given by the friction angle, which is constant for the model and therefore independent of the flow thickness.

Both models show a high number of simulations inundating the main channel of each barranca, especially in the proximal reaches of each drainage (e.g. ≤ 4 km). Further downstream, however, Volcflow simulations predominately propagate along the main incised channels staying relatively valley-confined – e.g., the confluence of Barranca Honda with the other southward flowing river (Guacalate) – while TITAN2D simulations, particularly those over 5-10 Mm³, result in simulation footprints that overflow the main channel sometimes inundating extensive areas adjacent to the channel (Fig. 4a, c). Overbanking in these simulations occurs in specific areas along the flow path, usually coinciding with the main break-in-slope at the foot of the main stratocone (4-5 km away from the summit) and/or at distinct bends in the valley axis. An important observation is that both PDC models identify the same areas as prone to overbanking, while the extent of overbanking is more extensive for TITAN2D and more limited for Volcflow simulations.

In Barranca Trinidad, points of interest A, B and C are all inundated by roughly 1/3 of the PDC simulations for both models. However, the characteristics of PDC inundation at these points vary depending on the model and this is explored in detail later in this section where we compare the zero-flow “isolines” – contours in input space separating simulations that lead to inundation from those that do not – of the modeled flows at all three points of interest. Resolving zero-flow isolines directly from simulations would require tens of thousands of simulations rendering this task infeasible, even with the comprehensive suite of simulations explored in this work. Instead, we use these simulations to train a zGP surrogate for each point of interest to further explore the intricacies of modeled PDC behavior. (Results of the zGP application are at the end of this section.)

The dimensionless ratio $A/V^{2/3}$, where A denotes the observed PDC area of inundation and V denotes measured PDC volume, is a *classic* metric to assess PDC mobility of natural flows (e.g. Calder et al. 1999), and can also be used here to look at simulated PDC mobility. Importantly, the links between model rheology parameters and simulated PDC mobility metrics, do show key differences between the two PDC

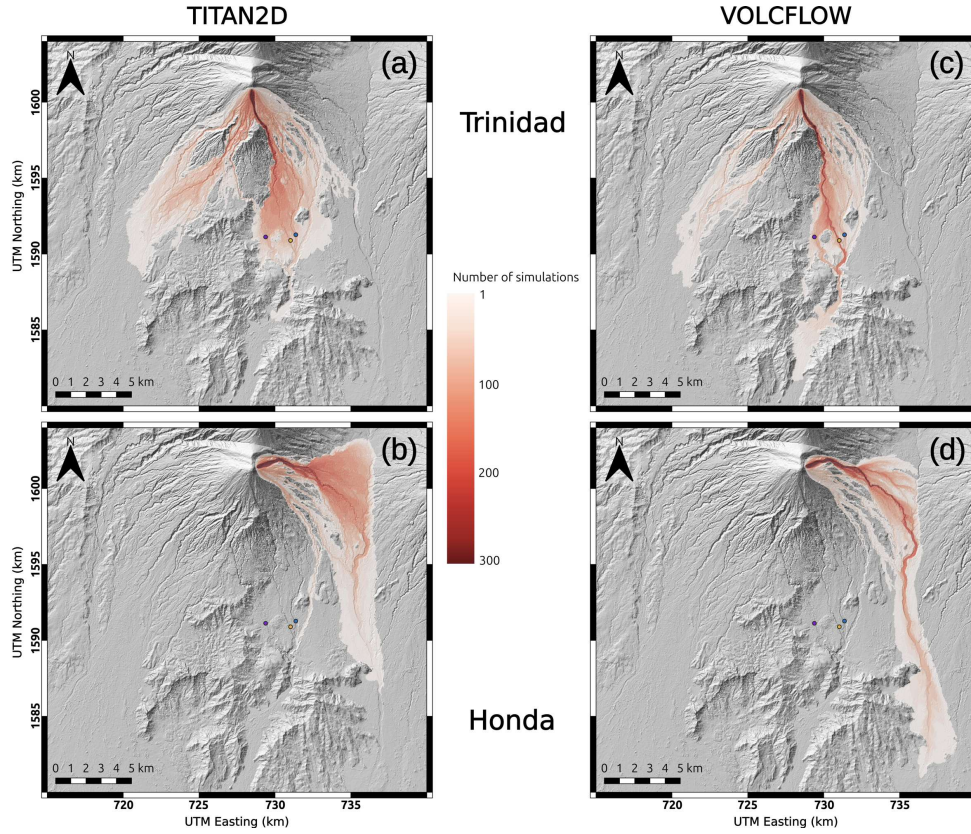


Fig. 4 Maps showing the cumulative inundation footprint of the design simulations run for the two PDC models (TITAN2D, a-b; and Volcflow, c-d) for two barrancas of interest (Trinidad, a, c; and Honda, b, d). NB. Points of interest A (purple), B (yellow) and C (blue) from Figure 1 are also displayed. Labels have been omitted as to not impede visualization of the cumulative inundation footprints..

models, particularly for the simulated $A/V^{2/3}$ metric (e.g. Ogburn et al. 2016) (Fig. 5). TITAN2D simulations, in both barranca Trinidad and Honda, show modest values of $A/V^{2/3}$ for Coulomb-type friction $\mu > 0.2$, and very sharp increase in $A/V^{2/3}$ for flow simulations of lower friction (i.e. higher simulated mobility) (Fig. 5a, c). For Volcflow, there is a general increase in $A/V^{2/3}$ with decreasing constant retarding stress (i.e. increasing simulated mobility), but the changes are considerably more gradual than in TITAN2D. These relationships holds not only for barrancas Trinidad and Honda, but for simulations undertaken in all the barrancas (Fig. S5 in S.3).

Extending the analysis to simulated PDC volumes (V), we define a new mobility metric, *the areal ratio*, as the ratio between the simulated PDC inundation areas with flow depth equal or greater than 100 cm (A_{100cm}) and greater than 10 cm (A_{10cm}). The $A_{100cm} : A_{10cm}$ ratio captures distal thinning, spreading or shearing

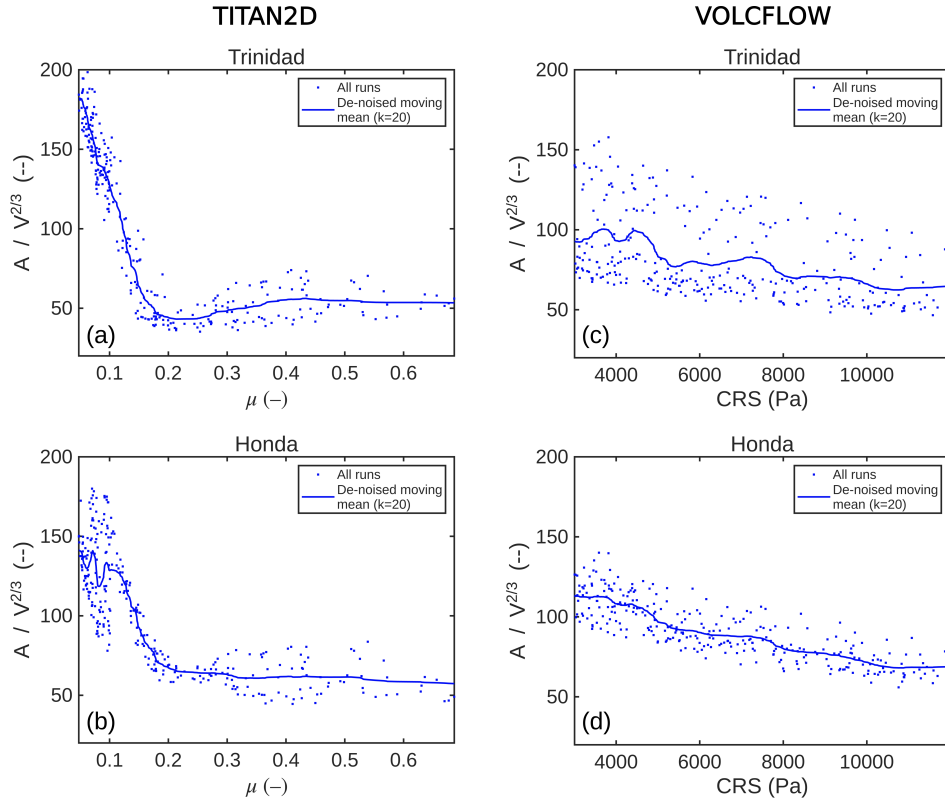


Fig. 5 Simulated $A/V^{2/3}$ mobility metrics as computed from the outputs of the design simulations for barrancas Trinidad (a, c) and Honda (b, d) versus model rheology parameters (TITAN2D: Coulomb friction parameter, μ , a-b; Volcflow: Constant Retarding Stress, CRS , c-d). NB. A , derived from simulation outputs, is calculated using a threshold of 10 cm in the simulated flow depth while V relates to specified volumes.

of the flows as the simulated flows come to rest, and again interesting differences can be seen in the behaviour of the two models (Fig. 6). The idea here is to identify which simulated inundation footprints are dominated by very thin, spread out flows which are indicated by smaller ratios. Overall value ranges of the metric do not differ greatly between the two PDC models with the majority of simulations sitting between 0.8-0.97. That said, the pattern of $A_{100cm} : A_{10cm}$ behaviors with increasing PDC volume between the two models is quite distinct. Volcflow simulations show a steady increase in this mobility metric, with increasing V , virtually insensitive to the barranca under consideration (Fig. 6c-d). That is, roughly, a smaller percentage of Volcflow footprints are spread thin with increasing volume. TITAN2D simulations on the other hand, show an initial increase, followed by a decrease then followed by a second segment of increase and this occurs in both barrancas Trinidad (Fig. 6a) and Honda (Fig. 6b). These decreases mainly results from an increase in A_{10cm} relative to A_{100cm} (Fig. S6), and occur at volumes of between 3-20 Mm³. Although the shape

of the curve is barranca-dependent, the minimum value of the ratio is roughly around $V = 10 \text{ Mm}^3$ and is similar for both of these barrancas. Note, we suspect that this minimum is both volcano and drainage dependent, but such a minimum reflects volumes at which TITAN2D flows become less channelized in these two barrancas. For both PDC models, at larger V , A_{100cm} continues to increase and the areal ratio becomes higher for both barrancas of interest (Fig. 6), i.e. distal flows have a smaller percentage of their footprints that are spread thin.

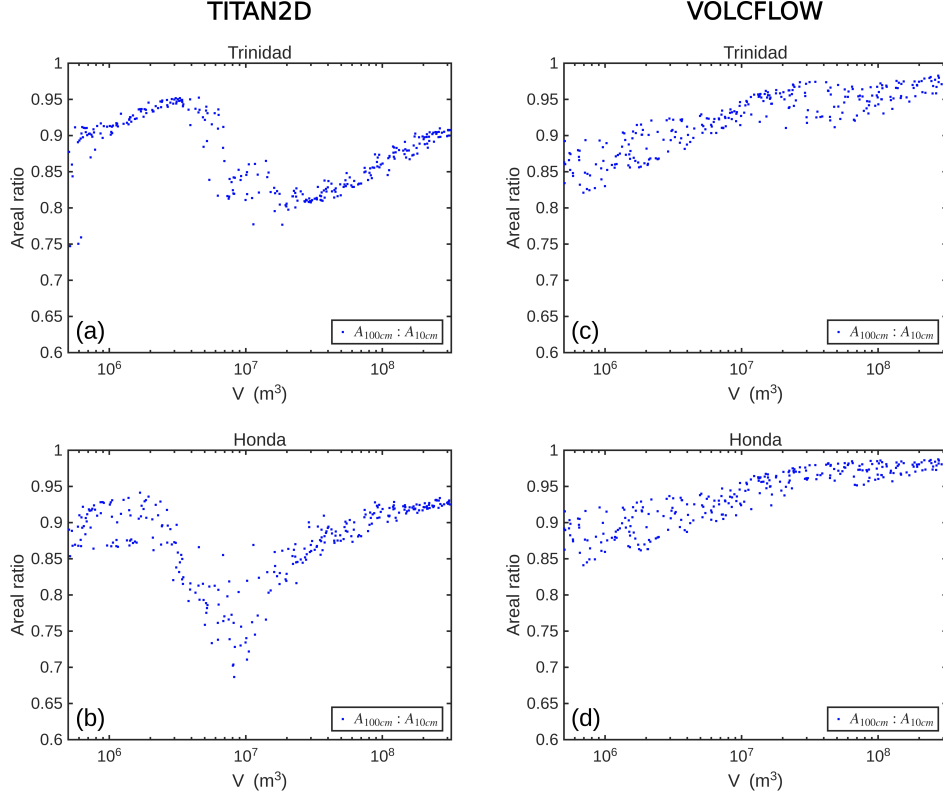


Fig. 6 A simulated PDC mobility metric (Areal ratio) – based on the ratio between the area inundated by PDCs with maximum thickness over 100 cm (A_{100cm}) and those with maximum thickness over 10 cm (A_{10cm}) – versus PDC volume (V), for the two PDC models explored (TITAN2D, a-b; and Volcflow, c-d) and two barrancas of interest (Trinidad, a, c; and Honda, b, d).

The areal ratios for TITAN2D suggest a change in simulated PDC behaviour in these barrancas at volumes around $3\text{-}20 \text{ Mm}^3$. To further explore this, we plot the cumulative extent of simulated flow footprints for PDCs with volumes either below or above 10 Mm^3 (Fig. 7). Simulated flows smaller than 10 Mm^3 remain highly channelized in Barranca Trinidad, independently of the model, although TITAN2D PDC footprints show some incipient overbanking, both proximally towards the SW and distally,

875 approximately coincident with the break-in-slope at the foot of the main stratocone
876 (Fig. 7a, e). In Barranca Honda, simulated flows smaller than 10 Mm³ show minimal
877 overbanking in Volcflow but some in TITAN2D. For both models, overbanking mainly
878 takes place around an area where a valley bend and a break-in-slope are coincident
879 (Fig. 7c, g). For simulated flows larger than 10 Mm³, both PDC models display PDC
880 footprints that cover extensive areas (up to almost 75 km² in some cases, Fig. S6),
881 producing significant overbanking along the entire flow paths in both barrancas (Fig.
882 7b, f, d, h).

883
884 Nevertheless, Volcflow outputs show PDCs that remain, for the most part, chan-
885 nnelized. The main channel(s) is identifiable by a greater number of simulations
886 inundating it compared to the surrounding, off-channel areas (Fig. 7f, h). This is not
887 the case for TITAN2D outputs, where the main channels are harder to distinguish
888 due to more widespread PDC overbanking (Fig. 7b, d). In Barranca Trinidad, this is
889 observed in proximal sectors (e.g. within 2 km from the source) as well as in medial
890 to distal sectors of the main channel up to 10 km from the source, and around where
891 the points of interest are located (Fig. 7b). In Barranca Honda, TITAN2D simulated
892 PDCs extensively overbank in the area also identified using the < 10 Mm³ simula-
893 tions, and then they fan out freely over the plain to the east (the Alotenango plain)
894 (Fig. 7). For TITAN2D, the PDC overbanking results in an area of approximately
895 15 km² with similar counts of simulations inundating in- and off-channel grid points,
896 when looking at large-volume flows (Fig. 7d). For Volcflow, the equivalent total
897 overbanking area is about 12 km², of which only the grid points relatively close (1-2
898 km) to the onset of PDC overbanking show high numbers of simulations inundating
899 those points (Fig. 7h). Interestingly, Volcflow simulations can re-channelize flows
900 after overbanking, as shown in the secondary channel running parallel to but north
901 of Barranca Honda over the Alotenango plain (Fig. 7h).

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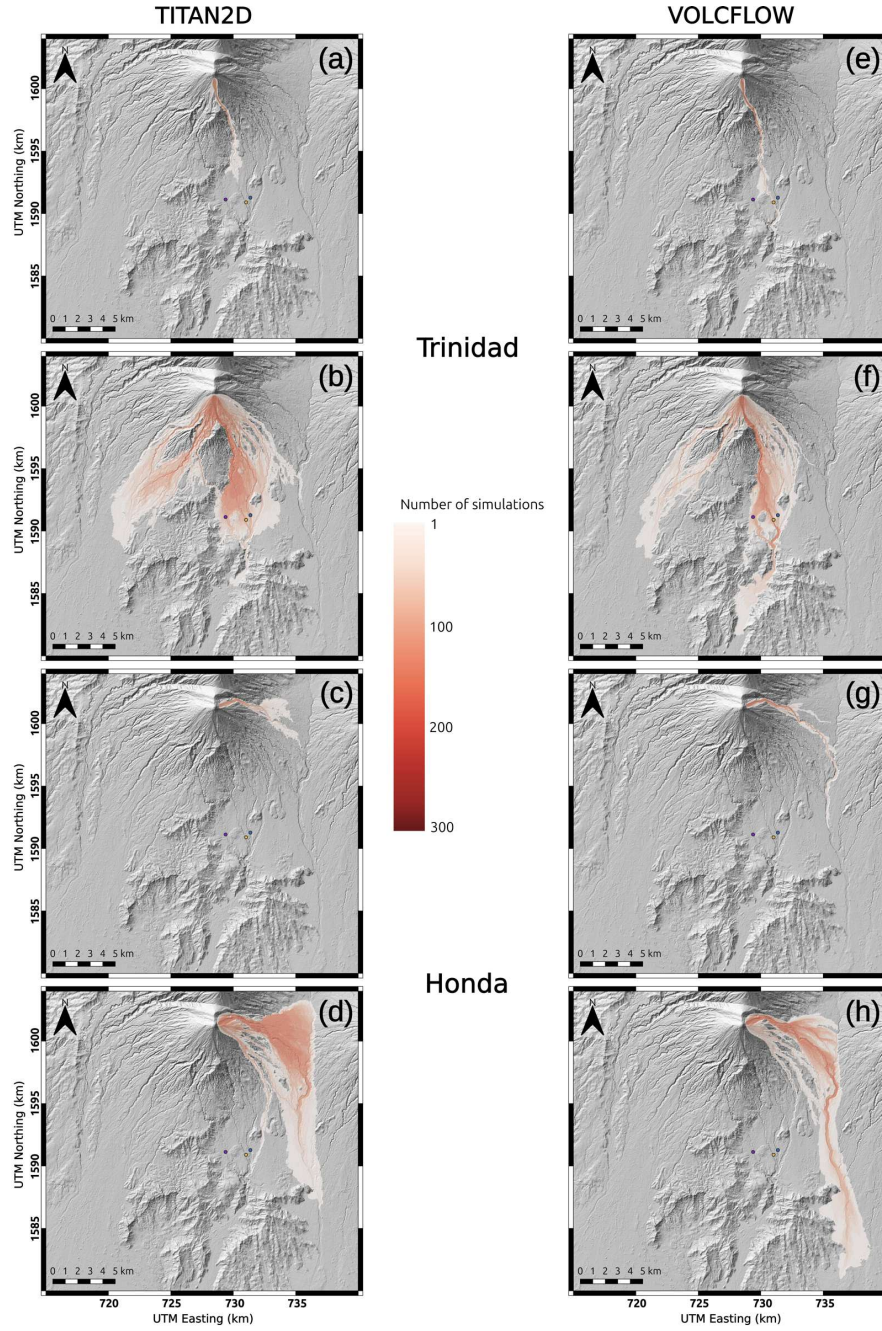


Fig. 7 Maps showing the cumulative areal extent of the design simulations run for the two PDC models explored (TITAN2D, a-d; and Volcflow, e-h) and two barrancas of interest (Trinidad, a-b, e-f; and Honda, c-d, g-h), after thresholding such simulations by PDC volume (V). Thus, insets a, c, e, g display the number of simulations whose flows inundate each grid point for PDCs of $V < 10 \text{ Mm}^3$, and insets b, d, f, h display such number for PDCs of $V > 10 \text{ Mm}^3$. The threshold chosen relates to results in Figure 6. NB. Points of interest A, B and C from Figure 1 are displayed in the same colors, but not labeled, to help visualization of PDC footprints.

967 Concerning the links between PDC volumes and another *classic* PDC mobility met-
 968 ric, H/L (e.g. Hayashi and Self 1992; Calder et al. 1999; Toyos et al. 2007; Ogburn
 969 et al. 2016), we observe significantly different results for simulated H/L between
 970 the TITAN2D and Volcflow models (Fig. 8). That is, TITAN2D outputs gradually
 971 change in terms of H/L versus PDC volume, towards more mobile (lower H/L) flows
 972 as volume increases, following the $V - H/L$ model (Ogburn et al. 2016) fitted on
 973 Fuego’s, and analogue volcanoes’ past-deposits data (Fig. 8a-b). This general pattern
 974 is, in part, the result of the chosen design (see Section 4 and Fig. S3), but each
 975 barranca of interest has a slightly different set of computed H/L values (Fig. 8a-b).
 976 In the case of Volcflow, H/L values are lower than for TITAN2D and vary more
 977 significantly as PDC volume increases. Further they maintain a pattern of increasing
 978 PDC mobility with increasing PDC volume (Fig. 8c-d), and varying CRS offers much
 979 less control over mobility in Volcflow than varying friction does in TITAN2D. The
 980 difference between the VolcFlow outputs and the the $V - H/L$ model (Ogburn et al.
 981 2016) fit to deposit data are quite significant. From a simulation design perspective,
 982 this stems from the lack of control over simulated flow mobility offered by varying
 983 CRS. As we see in Figs. 8a-b, most of the Volcflow (CRS) results fall outside the
 984 confidence interval and prediction interval bounds of the $V - H/L$ model, which is
 985 not the case for the Titan2D (Voellmy-Salm) results. This shows a systematic skew
 986 of the VolcFlow results towards lower H/L values, which implies that such results
 987 will reach longer runouts for given volume, making them significantly more mobile.
 988
 989 Despite H/L being a classical PDC mobility metric, as a scalar metric, it cannot
 990 properly capture the intricacies of a full PDC inundation footprint, natural or sim-
 991 ulated. Grid points located at similar distances from the source can, and often do,
 992 display different values of flow depth for the same simulated PDC. Further, simulated
 993 flows that inundate these similar-distance points have different links between PDC
 994 volume and rheology parameters, and the resulting flow depth. For example, these
 995 links can depend on whether the similar-distance points are located within the main
 996 channel or in an inter-channel area. To illustrate the nuances lost by relying solely
 997 on simulated, scalar mobility metrics, we employ a flexible yet powerful tool, the
 998 zero-censored Gaussian Process emulator (zGP) (Spiller et al. 2023) that allows us
 999 to interpolate between simulations in our design (Fig. 2). In Figure 9, we identify
 1000 which combinations of model input parameters (e.g. PDC volume and respective
 1001 rheology parameter) lead to PDC inundation at the three points of interest (A-C)
 1002 introduced in Figure 1. We do that by first fitting the emulators to the 300 design
 1003 simulations available for each of the PDC models (Fig. 2) for barranca Trinidad. We
 1004 fit one zGP emulator to the input/output of our training simulations (simulation
 1005 parameters/inundation depth) at each point of interest and for both PDC models,
 1006 six zGP emulators in total (Fig. 9). Once the emulators are fitted, their predictive
 1007 mean can be evaluated at any untested scenario within our 3-dimensional model
 1008 parameter space (V , d , and μ/CRS , depending on the PDC model) in a fraction of a
 1009 second to provide estimates of the flow depth at each point of interest. In particular,
 1010 we focus on mapping the zero-flow isoline within the V -rheology space – that is,
 1011 the line that separates simulations that result in PDC inundation from those that
 1012

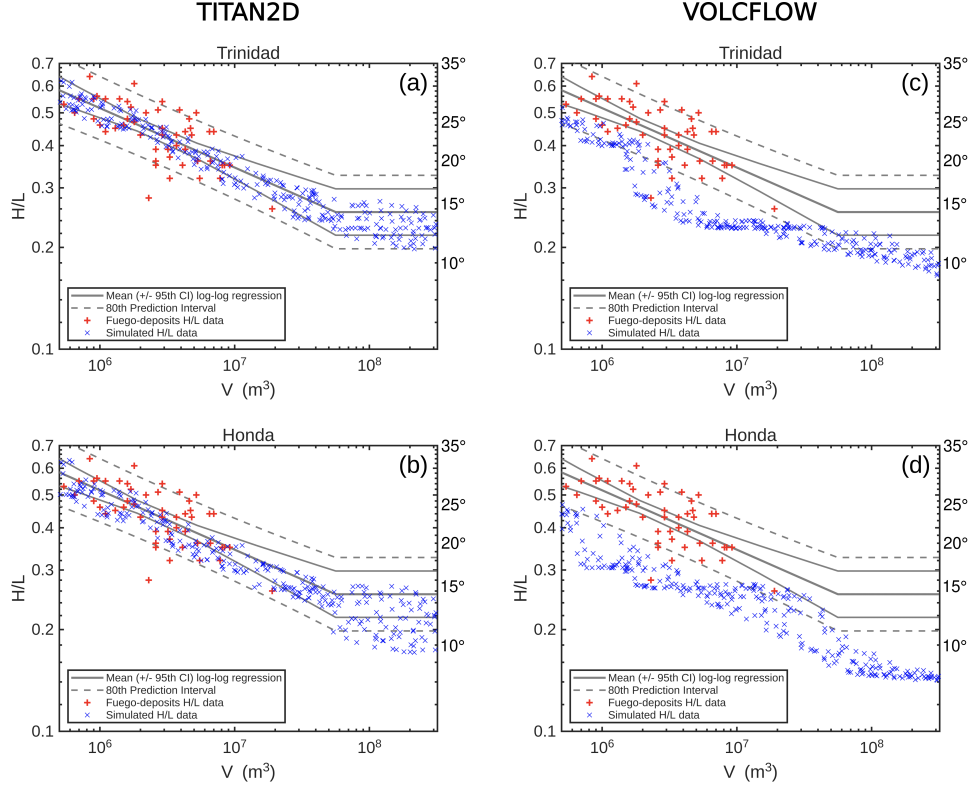


Fig. 8 Log-log relationships between the simulated PDC volume (V) and the H/L PDC mobility metric computed from the model outputs, for the two PDC models explored (TITAN2D, a-b; and Volcflow, c-d) and two barrancas of interest (Trinidad, a, c; and Honda, b, d); where L is the maximum runout of the flow, and H is the total vertical drop between flow source and maximum runout (e.g. Malin and Sheridan 1982). Results from a statistical model (grey lines) that fits V - H/L data from deposits of past PDCs at Fuego (red plus signs) and other analogue volcanoes, are shown for comparison (see Sections 4 and 7, and Figure S3 for more details).

do not, at the point of interest. Given that we incorporate the flux-source duration into our simulation-emulation strategy, we can evaluate where that isoline projects onto the aforementioned 2D space, for any value of the duration we want to choose. We illustrate this by choosing durations that, for each PDC volume evaluated, are near the lowest- and highest-duration edges within our design space (Fig. 2) given by Equations 2 and 3, respectively. To clarify, lowest and highest durations imply highest and lowest average volumetric fluxes for the PDC source as volumetric flux and duration are inversely proportional. In summary, to identify the zero-flow isolines, we fit six zGPs (one for each model and each location A, B, and C). Then we evaluate their respective predictive flow depths over two dense grids (one for low-duration curve and one for the high-duration curve) of $\sim 40k$ scenarios in V - μ/CRS space.

The results in Figure 9 exemplify how the zero-flow isolines change depending on: (i)

the location of the point of interest (off, A and C, or on the main channel, B); (ii) the PDC model explored, and (iii) the flux-source duration chosen (Fig. 9). For both PDC models, a link between PDC volume and the rheology parameter is observed, as PDCs which have higher values of the rheology parameters need to be larger in volume in order to inundate each of the points of interest (Fig. 9). One main difference between the PDC models is that, in Volcflow, a slight increase in the rheology parameter (CRS) only requires a moderately larger PDC volume for the point of interest to be inundated. In TITAN2D instead, a slight increase in the rheology parameter (μ) translates into PDCs needing to be considerably larger in volume to inundate the same point of interest. In other words, the slope of the V -rheology parameter zero isolines is steeper in Volcflow and flatter in TITAN2D (Fig. 9).

Comparing PDC models, similar patterns are observed between points of interest (see Fig. 1 for a reminder of their relative placement in the topography). Point A (off-channel to the west) shows higher dependence on the flux duration for larger volumes (i.e., wider area between zero-flow isolines) than for smaller volumes. Point C (off-channel to the east) shows very limited dependence on the flux duration across volumes (i.e., narrow area between zero-flow isolines). Finally, point B (on the main channel, although just out of the valley floor) shows a significant influence of flux duration, which is more or less constant across PDC volumes (Fig. 9). The final critical difference between TITAN2D and Volcflow comes from the *ordering* of the zero-flow isolines. In TITAN2D, off-channel locations A and C are inundated by PDCs of smaller volumes, while it takes larger PDC volumes to inundate the on-main-channel location B (Fig. 9b). For Volcflow, this ordering is opposite, and off-main-channel locations are generally inundated by PDCs of larger volumes, compared to volumes required to inundate the on-main-channel location B (Fig. 9a).

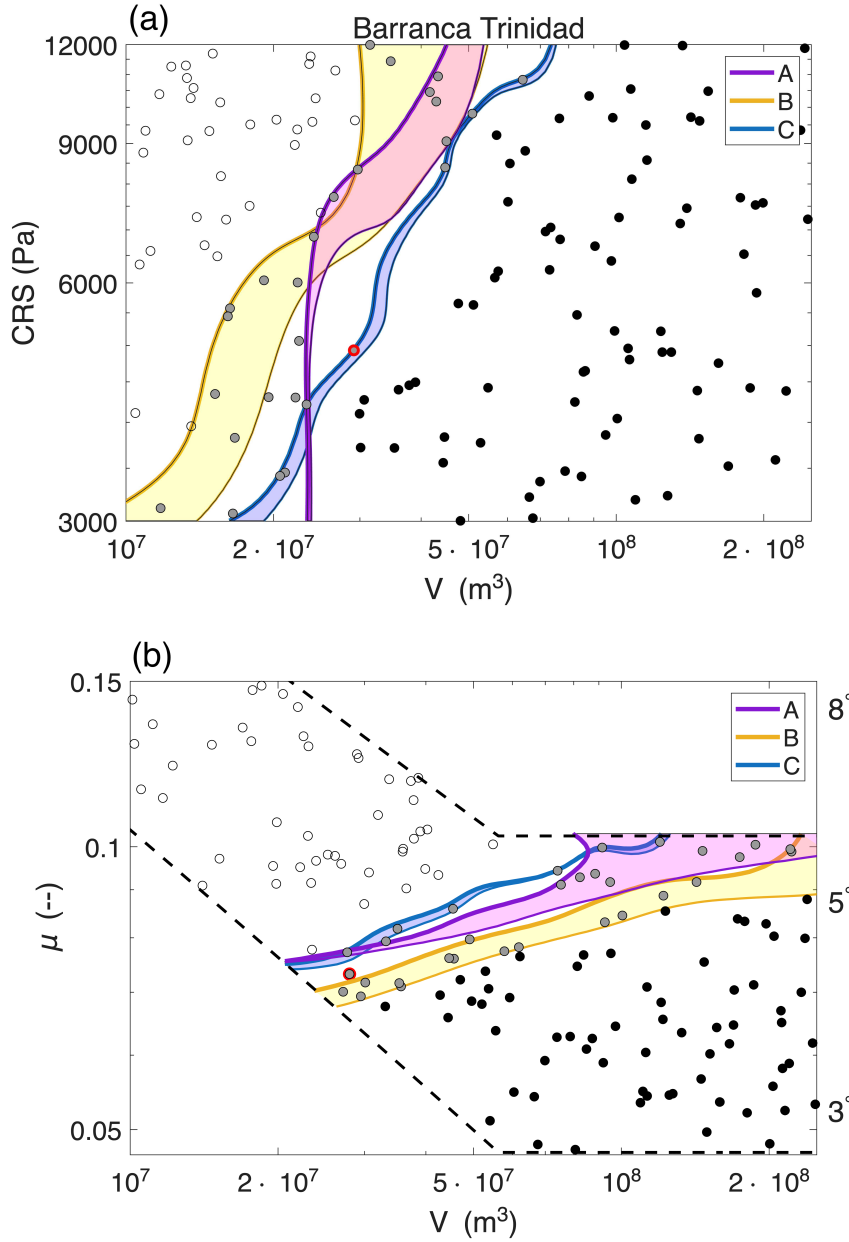


Fig. 9 Illustrative examples of how to use map-node-wise zGPs (Spiller et al. 2023) to calculate zero-flow isolines within the a) V - CRS (VolcFlow) or b) V - μ (TITAN2D) space for each point of interest. These isolines are calculated at the bounds of the duration design (dashed curves in Figs. 2a-b). For each location, the thicker curves correspond to the upper bound of the duration design while the thinner curves correspond to the lower bound. The simulation design in the volume-rheology parameter planes are indicated with dots. Empty dots correspond to PDC simulations with no inundation at any of the three locations of interest. Grey dots indicate that at least one point of interest was inundated by that simulation. Black dots are simulations that inundate all three points of interest. For reference, the red-circled dots are inputs corresponding to the simulations plotted in Figs. 3a and 3c.

1151 6 Discussion

1152
1153 Across the 3600 simulations presented here, the two PDC models outputs agree more
1154 than we anticipated. Within any given barranca the outer envelopes of the cumulative
1155 inundation footprints are broadly comparable (Figs. 4, S4) and, importantly, both
1156 models identify the same reaches and areas of each drainage as prone to overbanking.
1157 At first order, therefore, the dominant control on where simulated PDCs travel over
1158 the Fuego terrain is the topography of the individual barranca rather than the rheo-
1159 logical formulation used to move material through it. This is encouraging for hazard
1160 analysis broadly, because topography, in spite of its associated uncertainty, is both
1161 observable and incorporated into the PDC modeling process. The differences between
1162 the model outputs are found to be largely systematic, and are most significant in the
1163 medial-to-distal reaches, off-channel areas (where population exposure is highest),
1164 and can be traced to rheological and numerical implementation differences between
1165 Volcflow and TITAN2D.

1166
1167 **Differences between Volcflow and TITAN2D** The rheological property that
1168 primarily underpins the differences in outputs is whether basal resistance scales with
1169 flow depth. In Volcflow the retarding stress τ is constant, so the equivalent friction
1170 coefficient, $\tau/(\rho gh \cos \theta)$, varies inversely with flow depth. That is, a thick, channel-
1171 confined current is comparatively mobile, whereas a thin sheet which is overbanking
1172 is strongly retarded and arrests within a short distance (e.g. Kelfoun et al. 2009;
1173 Kelfoun 2011). The rheology is therefore intrinsically self-channelizing. In TITAN2D,
1174 by contrast, basal resistance in the Voellmy-Salm formulation is dominated by a
1175 constant Coulomb term and is independent of h , so whether material keeps moving
1176 is determined by the local slope relative to the friction angle. That is, a thin flow
1177 veneer that escapes the channel confinement can progress beyond the channel and
1178 over the interfluvial terrain as long as the ground beneath it is steeper than the angle
1179 corresponding to the inverse tangent of μ .

1180
1181 These different rheological formulations account for much of what we observe in the
1182 outputs and propagate into the relationships of their respective simulated mobility
1183 metrics. It explains the narrower, longer Volcflow footprints and the wider, shorter
1184 TITAN2D ones (Fig. 4), together with the ability of Volcflow currents to re-channelize
1185 after overbanking (for example on the Alotenango plain (Fig. 7h)). It explains the
1186 sharp increase in $A/V^{2/3}$ once μ falls below ~ 0.2 in TITAN2D (Fig. 5a-b), which
1187 marks where the friction angle drops below the gradient of Fuego's medial and distal
1188 flanks (beyond 6 or 7 km from the vent) and extensive in-channel and off-channel
1189 areas become accessible (and area increased by a factor of 5 or 6), whereas the equiv-
1190 alent transition in Volcflow is mediated by flow depth and is correspondingly gradual
1191 (Fig. 5c-d). It also explains why each model encodes its sensitivity in a different
1192 output variable. In TITAN2D the area of inundation carries the signal of changing
1193 volume and rheology while maximum runout varies smoothly, whereas in Volcflow
1194 the area varies smoothly and the maximum runout changes abruptly (Figs. 5, 6, 8).

1195
1196 Rheology is not the only source of divergence between Volcflow and TITAN2D,

however, since their respective codes (numerical approximations of the models and implementation choices) also differ in how they capture the flow-topography interaction. TITAN2D integrates the depth-averaged equations on an adaptive finite-volume mesh in a Cartesian frame with slope source terms, and includes a centripetal correction to the basal normal stress that depends on local terrain curvature. Volcflow advances the equations on a fixed grid with a simpler treatment of the terrain-normal direction (Patra et al. 2005; Kelfoun and Druitt 2005). Since curvature involves second derivatives of the DSM, TITAN2D is intrinsically the more sensitive of the two to breaks in slope, valley bends, and DSM resolution and smoothing (e.g. Ogburn et al. 2014). This matters because the topographic elements that control overbanking at Fuego, namely the break-in-slope at the foot of the cone and the sharp valley bends, are precisely those for which synthetic benchmarking has revealed the largest spread between the two depth-averaged codes, only part of it attributable to rheology (Gueugneau et al. 2021). Since each model is exercised with its own closure, our design cannot fully separate rheological from numerical contributions, and we do not attribute all of the differences described above to rheology alone.

What survives the ambiguity above, and is the most operationally useful result, is that the two models agree on *where* PDCs overbank and disagree only on *how much*. This should not be surprising given that both models share many fundamental assumptions, e.g. the conservation of flow volume, which is independent of the rheological formulation and the use of a common digital surface model. Volume conservation coupled with flow velocity decreasing down-slope, and abrupt decreases in channel confinement can result in overbanking of flows at similar locations for both models. Overbanking location is topographically determined and identified consistently by both codes, in barrancas Trinidad and Honda, and even by some of the the small-volume ($< 10 \text{ Mm}^3$) subsets (Fig. 7), whereas areal extent of overbanking is rheology-dependent ($\sim 15 \text{ km}^2$ for TITAN2D against $\sim 12 \text{ km}^2$ for Volcflow in Barranca Honda). For hazard assessment purposes, the two models can be read as bracketing behaviors. TITAN2D provides an upper bound on lateral spreading and Volcflow a lower one, while the locations they flag are independent of model choice. One caveat deserves emphasis. Flow overbanking that occurred during the 3 June 2018 eruption, was driven by the valley-filling deposition of earlier flows in the sequence of flows happening that day – and by subsequent overspill of both the concentrated layer and its dilute overriding cloud, (Charbonnier et al. 2023), a mechanism neither model here can directly capture.

These observations bear on how model performance should be judged, and here the metrics themselves are part of the difficulty. The clearest illustration is the relationship between the friction coefficient supplied to TITAN2D and the H/L of its simulations return (Fig. S3b). Were the classical energy-line equivalence to hold, the two would coincide. Instead, every simulation in all six barrancas, returns an H/L above the input μ , and the discrepancy widens as μ decreases, from near equality at $\mu \approx 0.6$ to a factor of three or more at $\mu = 0.05$. Part of the gap is geometric, since H/L is measured from summit to flow tip while the current travels a longer, sinuous

1243 path down the barranca. The remainder is dissipation that the energy line does
1244 not account for, including the velocity-dependent term and the momentum spent
1245 spreading laterally and overbanking. Consequently, a rheological parameter cannot
1246 be read as a mobility metric, and calibrating μ directly against observed H/L , as
1247 the one-to-one assumption of Ogburn (2014) would suggest, is not suitable for this
1248 study. It is precisely why the design used here is shifted and tilted away from that
1249 relationship (Fig. S3a and Sect. 7), so as to return simulated H/L values consistent
1250 with Fuego’s deposits at small volumes and with the hierarchical model at large ones.
1251 For the Volcflow results, the fit to the H/L metric is often an underestimate. Further,
1252 simulated mobility as measured by H/L is not readily controllable by varying CRS.
1253 The VolcFlow results mostly fall below the confidence and prediction intervals of the
1254 $V - H/L$ hierarchical model, implying higher mobility and longer runout lengths.
1255 That said, many of the Volcflow H/L underestimates occur for volumes where the
1256 H/L model relationship is in the extrapolation regime.

1257

1258 **Flow model limitations and alternative options.** Several of the differences
1259 mentioned above stem from modeling limitations. Both models used here are single-
1260 layer and concentrated-flow, whereas PDCs are generally considered to be stratified,
1261 and a model that resolves that structure would allow the dilute overriding cloud
1262 that can inundate wider areas to be simulated explicitly. A two-layer extension of
1263 IMEX_SfloW2D currently in development offers one such route (de’ Michieli Vitturi
1264 et al. 2019, 2023; Breard et al. 2026). The scheme treats the friction terms implicitly,
1265 so that thin layers decelerate and arrest as part of the solution rather than through
1266 a tuned stopping criterion. Given that TITAN2D models “live” flows and that up to
1267 10 to 20 percent of the TITAN2D footprint correspond to between 10 cm to 100 cm
1268 maximum flow depth (Figs. 6 and S6), modeling improvements may be significant
1269 for hazard-relevant outputs.

1270

1271 Recent developments in IMEX_SfloW2D introduce a physically consistent granular
1272 rheology in which frictional resistance evolves dynamically through transient pore-
1273 pressure diffusion and its coupling to the granular state. This shifts the problem
1274 toward model parameters with direct physical interpretability including the friction
1275 coefficient, initial pore pressure, pressure diffusivity and flow temperature. Fur-
1276 ther, uncertainty in these parameters can be characterized, at least in principle, by
1277 independent experimental or field constraints. Future applications should therefore
1278 extend the ensemble strategy developed here to these physical parameters, allowing
1279 uncertainty in measurable material and flow properties to be propagated directly into
1280 predictions of mobility and, critically for Fuego, overbanking. Lastly, IMEX_SfloW2D,
1281 shares many of the features of TITAN2D and Volcflow that make those amenable
1282 to a similar design of experiments – the model is parsimonious but computationally
1283 expensive, making it an excellent candidate to use in conjunction with stochastic
1284 surrogates, like the zGP, in future PVHA.

1285

1286 **Development of the workflow towards probabilistic hazard maps.** The
1287 framework developed here provides the basis for the next stage of PVHA at Fuego,
1288

since the results above constitute a designed exploration of scenario space rather than a probability-weighted ensemble. Next we will develop models for the probability of PDCs of different volumes, durations and rheological parameters and undertake Monte Carlo simulations to explore the probability of inundation. We further need to devise a strategy for merging barranca-wise inundation probabilities, and inundation probabilities from both physical models, into hazard maps. The zero-flow isolines of Fig. 9 make the first component tractable because, once a zGP is fitted, any candidate scenario pdf can be propagated to an exceedance probability at a point of interest in a fraction of a second. The continued sensitivity of these isolines to flux-source duration even 10 km from the summit, together with the opposing ordering of on-channel and off-channel locations produced by the two models, shows that both source conditions and model structure influence simulated flow inundation footprints.

Hazard and risk implications. The two types of model behaviour combined with the particular Fuego channel geomorphology have important implications for determination of hazard and, when population distribution is taken on board, eventually risk. Populated areas tend to be located along the roads around the break in slope at the foot of the main stratocone (starting at distances of 6 to 7 km from summit), and are also located on the interfluvial terrain between the drainage channels, and as such both flow runout and potential flow overbanking are important factors in determining the extent to which populated areas are exposed to PDC hazard.

Channel morphology tends to evolve from that of relatively low confinement on the uppermost slopes in and around the summit (< 2 km), to large channel cross sections and depths in the medial reaches (2 to 7 km), followed by a reduction of channel cross section and depth at more distal reaches (> 7 km). For any given flow, it is clear that the most threatening scenario for the close communities that are located in the interfluvies, is that of overbanking in the distal portion. On the other hand, flows that spread across a wider area earlier are subsequently less likely to extend so far and reach the larger centres of populations at distances of 10-20 km. Conversely, a flow that remains confined in the upper reaches has increased likelihood of reaching a longer runout, possibly extending to locations where channel cross section and depth become small, at which point overbanking potential may increase again. Going forward, to use this work to progress a robust hazard and risk assessment will require a full analysis that takes into account the modeling, statistics and uncertainty but also the terrain, particularly the barrancas channel morphology, as well as the distribution of exposed population and infrastructure.

7 Conclusions

We developed a systematic, multi-model framework for exploring pyroclastic density current inundation scenarios for Fuego volcano, Guatemala, as a foundation for probabilistic hazard assessment. The 3600 simulations generated with TITAN2D and Volcflow shallow-water models span the six major drainage systems (barrancas) around the volcano and broad ranges of PDC volume, flux-source duration and

1335 model-specific rheological parameters. The space-filling design does not assign prob-
1336 abilities to individual scenarios, but provides a comprehensive catalogue of plausible
1337 behaviours from which source, topographic and model uncertainties can subsequently
1338 be quantified.

1339

1340 For individual barrancas, the two models produce broadly comparable outer inunda-
1341 tion envelopes and identify the same breaks in slope, channel bends, constrictions and
1342 drainage confluences as locations prone to, or that can induce, overbanking. Barranca
1343 geometry therefore provides the dominant first-order control on PDC pathways at
1344 Fuego. However, the magnitude and spatial extent of overbanking for the simulated
1345 flows remain strongly model dependent. TITAN2D generally produces wider, shorter
1346 footprints with more extensive off-channel spreading, whereas Volcflow produces
1347 narrower, longer and more strongly channelised flows. These contrasts arise largely
1348 because Volcflow’s equivalent basal resistance increases as the current thins, strongly
1349 retarding overbanking sheets, while the dominant Coulomb resistance in TITAN2D is
1350 independent of flow depth. The models can therefore be understood as representing
1351 contrasting end-member behaviours rather than as alternatives from which a single
1352 preferred model should be selected.

1353

1354 Our results also show that scalar mobility metrics from the simulated flows provide
1355 only a partial description of simulated PDC behaviour. As H/L cannot capture the
1356 spatial distribution of flow depth or distinguish channelised transport from widespread
1357 thin inundation, we introduce a new areal ratio, $A_{100cm} : A_{10cm}$. This ratio provides
1358 complementary information by quantifying the degree of distal thinning, or spreading.
1359 In TITAN2D, its minimum near 10 Mm^3 for barrancas Honda and Trinidad (Fig. 6)
1360 marks a rough transition at which currents begin to escape topographic confine-
1361 ment and spread rapidly as thin sheets. Importantly, this speaks to the relationship
1362 between flow volume and the nature of the retaining capacity of the draining systems
1363 around Fuego, rather than an inherent volume that’s relevant to TITAN2D. At other
1364 volcanoes, with different styles and volumetric capacity of drainages, we would expect
1365 this minimum value (as simulated by TITAN2D) to change.

1366

1367 Zero-censored Gaussian-process emulators provide an efficient means of retaining
1368 the nonlinear and spatial information contained in the numerical simulations. The
1369 resulting zero-flow isolines for three locations show how the volume, duration and
1370 rheological conditions required for inundation vary among on-channel and off-channel
1371 locations. Flux-source duration can influence inundation approximately 10 km from
1372 the summit, while model structure (e.g. rheological assumptions) can alter the rel-
1373 ative susceptibility of different locations. Both source conditions and model choice
1374 should therefore be carried explicitly as uncertainties into future hazard assessment
1375 calculations.

1376

1377 The results remain conditional on the model assumptions and topography used here.
1378 Neither model resolves the physics of the initial failure process, erosion, deposition,
1379 transient pore-gas pressure or coupling between a concentrated basal current and a
1380

dilute overriding cloud. The simulations are also tied to the drainage configuration represented by the digital elevation model used, whereas future channel infilling, erosion or avulsion could substantially alter PDC pathways. These are all limitations typical for any hazard assessment undertaken for PDCs on any given topography. Further, a close inspection of the DSM as well as patterns observed in our results highlight some potential artifacts in the DSM. The most significant artifact is a few km past point B in the main of barranca Trinidad (see Fig. 4). Fortunately, its location only impacts a few of the largest-volume Volcflow runs. Further investigation of potential DSM artifacts will be undertaken prior to future PVHA.

The next step in our broader workflow is to combine this simulation-emulation framework with probability models for PDC volume, duration, source barranca and uncertain rheological or model parameters, and then integrate barranca-specific probabilities into multi-barranca exceedance and hazard maps. By propagating both source and model-structural uncertainty, the approach developed here provides the basis for undertaking fully probabilistic assessment of PDC inundation at Fuego, a method which is transferrable to other persistently active, topographically complex volcanoes.

List of abbreviations

CRS	constant retarding stress
DTM	digital terrain model
DSM	digital surface model
GCRF	Global Challenges Research Fund (UK)
GP	Gaussian process
PDC	pyroclastic density current
pdf	probability density function
PVHA	probabilistic volcanic hazard analysis
QOI	quantity of interest
zGP	zero-censored Gaussian process

Declarations

Availability of data and materials

- Estimated volume and H/L data for PDCs of volume greater than 0.5 Mm^3 at Fuego (and plotted in Fig. S6) is available in Additional file 1.
- Simulation data may be available upon request. Subsequent to the planned full PHVA, it is the authors' intent that simulation data will be made publicly available in a repository.

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1436 **CRedit (Contributor Roles Taxonomy) author statement**

1437
1438 Elaine Spiller: Conceptualization, Methodology, Project administration, Supervision.
1439 Pablo Tierz: Methodology, Software, Resources.
1440 Sylvain Charbonnier: Methodology, Software, Resources.
1441 Eric Breard: Methodology, Software, Resources.
1442 Rüdiger Escobar-Wolf: Data Curation, Funding acquisition.
1443 Eliza Calder: Conceptualization, Supervision, Project administration, Funding acqui-
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