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Long-Term Probabilistic Volcanic Hazard Assessment Using Open and Non-open Data: Observations and Current Issues

*Pablo Tierz**†

British Geological Survey, The Lyell Centre, Edinburgh, United Kingdom

Probabilistic volcanic hazard assessment (PVHA) has become the paradigm to quantify volcanic hazard over the last decades. Substantial aleatory and epistemic uncertainties in PVHA arise from complexity of physico-chemical processes, impossibility of their direct observation and, importantly, a severe scarcity of observables from past eruptions. One factor responsible for data scarcity is the infrequency of moderate/large eruptions; other factors include lack of discoverability and accessibility to volcanological data. Open-access databases can help alleviate data scarcity and have significantly contributed to long-term PVHA of eruption onset and size, while are less common for data required in other PVHA components (e.g., vent opening). Making datasets open is complicated by economical, technological, ethical and/or policy-related challenges. International synergies (e.g., Global Volcanism Program, WOVOdat, Global Volcano Model, EPOS) will be key to facilitate the creation and maintenance of open-access databases that support *Next-Generation* PVHA. Additionally, clarification of some misconceptions about PVHA can also help progress. Firstly, PVHA should be understood as an expansion of deterministic, scenario-based hazard assessments. Secondly, a successful PVHA should sometimes be evaluated by its ability to deliver useful and usable hazard-related messages that help mitigate volcanic risk. Thirdly, PVHA is not simply an end product but a driver for research: identifying the most relevant sources of epistemic uncertainty can guide future efforts to reduce the overall uncertainty. Broadening of the volcanological community expertise to statistics or engineering has already brought major breakthroughs in long-term PVHA. A vital next step is developing and maintaining more open-access datasets that support PVHA worldwide.

Keywords: probabilistic volcanic hazard assessment, uncertainty quantification, data scarcity, open data, global databases

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Edited by:
Fidel Costa,
Nanyang Technological University, Singapore

Reviewed by:
Mark Bebbington,
Massey University, New Zealand
Chris Newhall,
Mirisbiris Garden and Nature Center, Philippines

****Correspondence:***
Pablo Tierz
pablo@bgs.ac.uk

†ORCID:
Pablo Tierz
orcid.org/0000-0001-8889-9900

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INTRODUCTION

Nearly 300,000 people died due to volcanic activity from 1600 to 2010 AD (Auker et al., 2013). Unfortunately, several other deadly eruptions have shocked the world since then. Some because of their lack of clear precursory evidence: Mayon, Philippines, in 2013 (Maeda et al., 2015). Others because of the magnitude of their destructive toll: Fuego, Guatemala, in June 2018

(Naismith et al., 2019) and Krakatau, Indonesia, in December 2018 (Grilli et al., 2019; Williams et al., 2019). One of the most infamous examples of volcano tragedy was the eruption of Mount Pelée, Martinique, in 1902, which claimed the life of around 30,000 people at St Pierre and Morne Rouge (Lacroix, 1904; Fisher et al., 1980). At the time of the eruption, it was assumed that "Mount Pelée would behave in 1902 as it had in 1851 – when a rain of ash [...] did not harm those living under its shadow" (Reed, 2002). However, the timing, location, size and style of volcanic activity tend to change from eruption to eruption and within the same eruption. Thus, properly accounting for and quantifying this natural variability, or aleatory uncertainty, of volcanic eruptions and their associated hazardous phenomena is a basic requirement for volcanic hazard assessment (e.g., Woo, 1999; Connor et al., 2001; Marzocchi et al., 2004). Such assessments should also quantify the epistemic uncertainty related to incomplete knowledge (e.g., Marzocchi et al., 2004; Rougier and Beven, 2013; Tierz et al., 2016a). This can be achieved through probabilistic analyses of the onset, size and location of volcanic eruptions, as well as of the spatio-temporal intensity of hazardous phenomena such as pyroclastic density currents (PDCs) or lahars. Probabilistic volcanic hazard assessment (PVHA) started to develop several decades ago (e.g., Newhall, 1982; Barberi et al., 1990; Connor and Hill, 1995; Connor et al., 2001; Newhall and Hoblitt, 2002; Aspinall et al., 2003; Sparks, 2003) and has now become the standard method for robust, accurate and complete volcanic hazard assessment worldwide (e.g., Marzocchi et al., 2008, 2010; Bayarri et al., 2009; Sobradelo and Martí, 2010; Jenkins et al., 2012; Marzocchi and Bebbington, 2012; Bebbington, 2013, 2014; Del Negro et al., 2013; Hincks et al., 2014; Connor et al., 2015; Neri et al., 2015; Newhall and Pallister, 2015; Whelley et al., 2015; Bevilacqua et al., 2016; Biass et al., 2016; Mead and Magill, 2017; Tierz et al., 2017; Sandri et al., 2018).

Carrying out PVHA requires the collection and use of volcanological data (**Figure 1**) to select and parameterize probability distributions to calculate volcanic hazard, including the critical sources of uncertainty (e.g., Connor and Hill, 1995; Aspinall, 2006; Marzocchi et al., 2008, 2010; Marzocchi and Bebbington, 2012; Bebbington, 2013; Tierz et al., 2016a,b). While these tasks are very data demanding, the vast majority of volcanic systems in the world remain data scarce (e.g., Loughlin et al., 2015). Open data are crucial to help alleviate the widespread issue of data scarcity and, hence, support advancement of PVHA. For instance, open data can be used to *borrow* useful information from *analogue volcanoes* (i.e., volcanoes that have enough similar characteristics as to be considered partially exchangeable) and apply it to perform PVHA at a specific (data-scarce) target volcano (e.g., Marzocchi et al., 2004; Bebbington, 2014; Sheldrake, 2014; Ogburn et al., 2016a; Sheldrake et al., 2016; Newhall et al., 2017; Tierz et al., 2019). Some open-access volcanological databases that contain the necessary data to compute PVHA are currently available: Volcanoes of the world, Global Volcanism Program (Siebert et al., 2010; hereinafter GVP)[1]; WOVOdat (Newhall et al., 2017)[2]; Large Magnitude Explosive Volcanic Eruptions (Crosweller et al., 2012; hereinafter LaMEVE)[3] and others. However, the majority of the volcanological community still heavily relies on non-open data to perform PVHA (e.g., Bevilacqua et al., 2016; Jaquet et al., 2017; Tierz et al., 2018). The predominant use of non-open data reduces the versatility and scope of PVHA methods because researchers worldwide may find it difficult to gain independent insights from the same datasets. Conversely, open-access datasets permit such complementary research to be developed (e.g., Deligne et al., 2010; Sheldrake and Caricchi, 2017; Papale, 2018; Rougier et al., 2018).

In this contribution, I explore the use of open and non-open data in long-term PVHA (i.e., volcanic hazard forecasts on the timescale of years to decades, Marzocchi and Bebbington, 2012) to evidence how the key issue of data scarcity manifests in the predominant and uneven use of non-open data across different components of the probabilistic assessment. Then, I discuss the importance of data scarcity and misconceptions around PVHA as current issues that collectively hinder further and wider development in the field. Finally, I suggest a few potential future directions in the view of an increased availability of open-access datasets to perform long-term PVHA at the individual volcano, regional and global scales.

OPEN AND NON-OPEN DATA IN LONG-TERM PVHA

I have selected a collection of 100 peer-reviewed contributions to analyze long-term PVHA research since 2001 (see **Supplementary Material**). The collection covers, without over-representation, the spectrum of different research groups, volcanic systems, types of PVHA and hazardous phenomena. Although it is not necessarily statistically representative in terms of stratified random sampling, it nevertheless serves to illustrate certain research trends in PVHA over the last two decades. This collection, which I will henceforth denote as the "Sample" is analyzed (**Figure 2**; and **Supplementary Material**), focusing on the use of open, non-open and mixed (i.e., both open and non-open) datasets (see **Definitions**) to assess different components of the long-term forecast: (1) eruption onset and size; (2) eruption vent location; (3) eruption impacts (by hazardous phenomena); and (4) combinations of any of the three, which I term *integrated PVHA*. In the Sample, studies that use either non-open or mixed datasets dominate over those using open datasets to compute long-term PVHA (**Figures 2A,B**). According to the Sample, there have not been major changes in the use of open, non-open and mixed datasets over time (**Figure 2C**).

Eruption Onset and Size

It is the only component of the hazard assessment where open data have been used in isolation (**Figure 2B**) and non-open and mixed data do not dominate (**Figure 2A**). Global databases of the timing and size of volcanic eruptions (principally GVP and

[1] http://www.volcano.si.edu

[2] https://www.wovodat.org/

[3] https://www.bgs.ac.uk/vogripa/view/controller.cfc?method=lameve

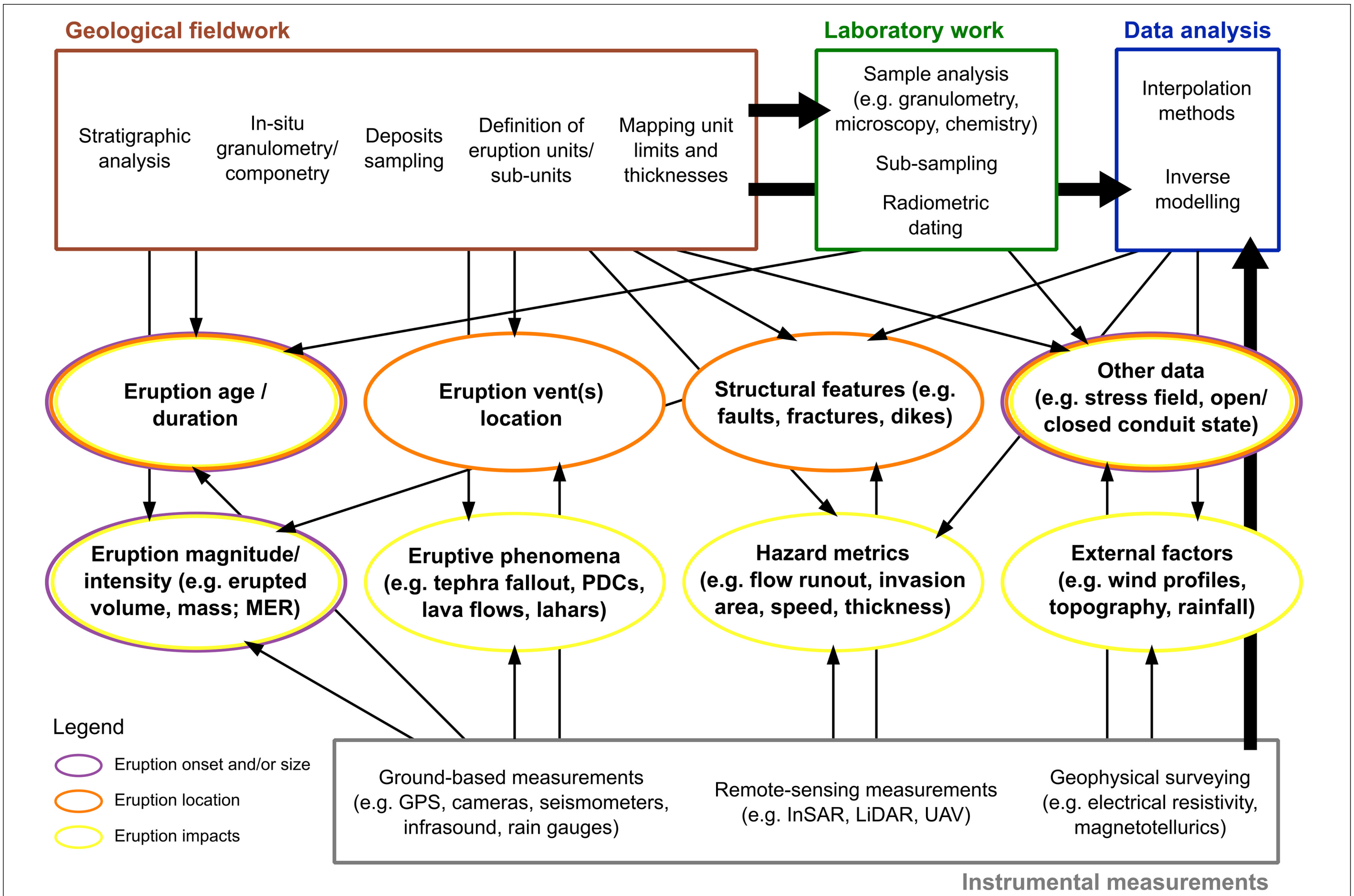

FIGURE 1 | Schematic showing the main types of data (ellipses) that are required to carry out long-term PVHA and some intermediate methods or steps (rectangles) needed to obtain these data. Arrows indicate links between intermediate steps or with derived PVHA data types and variables (ellipses and text within parentheses). Data types are classified according to their use in different components of the hazard assessment: eruption onset and/or size, eruption location and eruption impacts. The majority of the data are generated, directly or indirectly, through geological fieldwork performed on the eruptive products of past volcanic eruptions. Since historical times, direct observations and instrumental measurements of both eruptive parameters as well as external factors (e.g., wind, rainfall, topography) have also become available. MER, Mass Eruption Rate; PDCs, Pyroclastic Density Currents; GPS, Global Positioning System; InSAR, Interferometric Synthetic Aperture Radar; LiDAR, Light Detection And Ranging; UAV, Unmanned Aerial Vehicle.

LaMEVE) have been the key element required for the hazard analysts to conduct PVHA. The Sample suggests that eruption onset-size forecasts were more common during approximately the first decade of the 21st century (**Figure 2D**). This relative decrease could be partially explained by the incorporation of onset-size assessments into integrated PVHA over the second decade of the century (e.g., Sandri et al., 2012, 2014, 2018; Bartolini et al., 2015; Bevilacqua et al., 2017). Recent advances in PVHA of eruption onset and size have focused on alleviating issues around under-recording (Mead and Magill, 2014; Rougier et al., 2016; Sheldrake and Caricchi, 2017) and on the use of covariates to inform the statistical modeling: e.g., open/closed-conduit states (Bebbington, 2014; Whelley et al., 2015); rock geochemistry (Passarelli and Brodsky, 2012); volcano type or tectonic setting (Sheldrake, 2014; Sheldrake and Caricchi, 2017); or a combination of volcanological observations (Dzierma and Wehrmann, 2010, 2014). Moreover, advanced stochastic models to incorporate the epistemic uncertainty in the rates of eruption onsets, and model varied patterns of clustering and recurrent behavior of volcanic eruptions, have been proposed (e.g., Garcia-Aristizabal et al., 2012; Bebbington, 2013; Bevilacqua et al., 2016, 2018).

Eruption Vent Location

It has been exclusively performed using non-open data, according to the Sample (**Figure 2A**). This is strongly related to the fact that the detailed geological data (**Figure 1**) required to derive statistical models for the spatial occurrence of vent locations (e.g., Cappello et al., 2012; Connor et al., 2012; Selva et al., 2012b; Bevilacqua et al., 2015), are rarely available as open-access datasets. The data are available at specific volcanic systems but generalizations about the data-generating process for eruption location are hindered because of the lack of cross-volcano, open-access databases (NB. Le Corvec et al., 2013, could be considered as a "non-open archetype" for such databases). Some recent developments have looked at: (i) constraining the areal extent of vent locations by matching it to potential magma sources identified from geophysical imaging (Deng et al., 2017); or (ii)

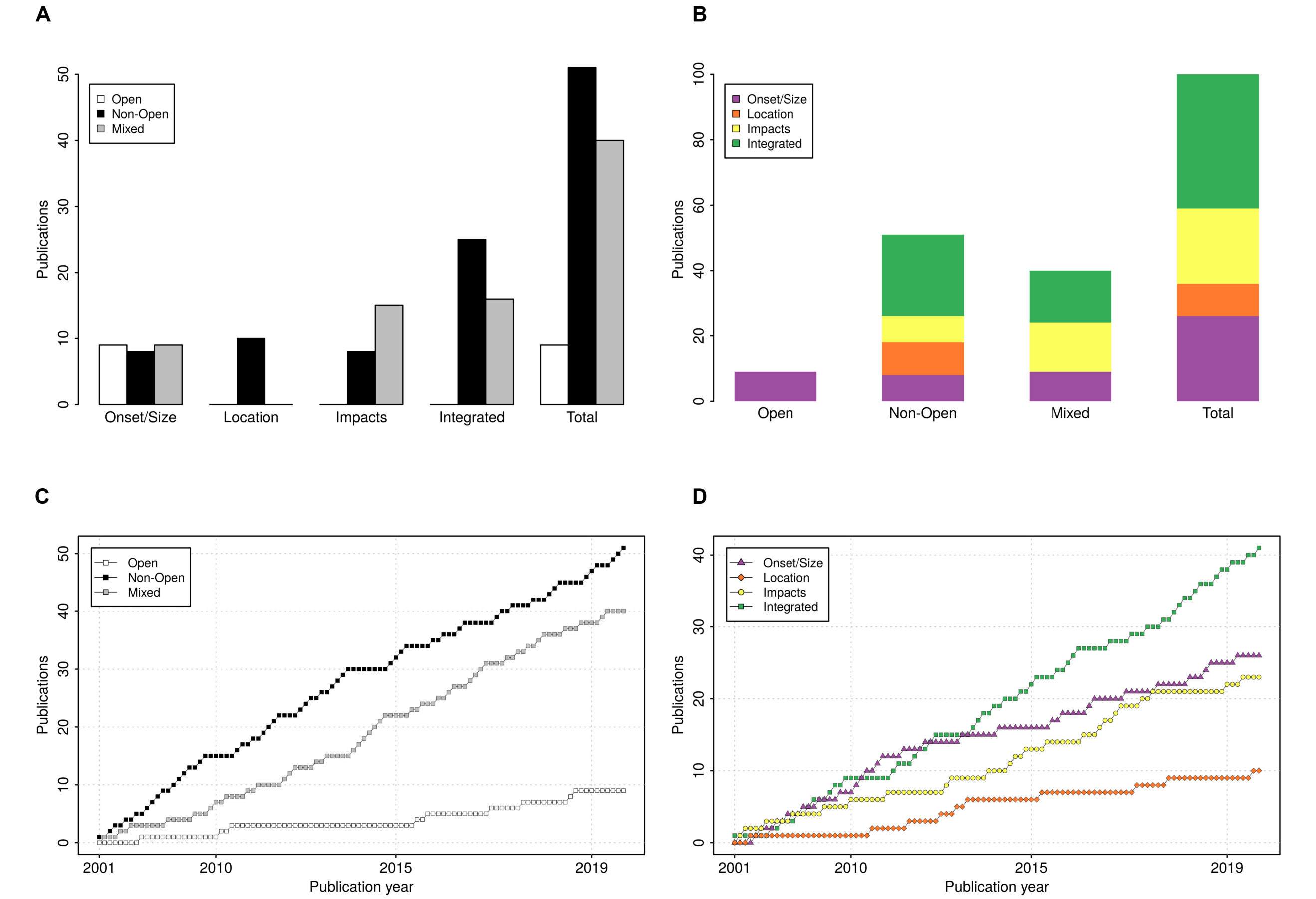

FIGURE 2 | Summary of patterns observed on a collection of 100 publications on long-term PVHA published since 2001. In **(A,B)**: total number of publications partitioned according to the use of open, non-open and mixed datasets **(A)**; and the focus of the PVHA: eruption onset and/or size, eruption location, eruption impacts or integrated PVHA **(B)**. In **(C,D)**: cumulative number of publications according to the same partitions: type of data **(C)** and focus of the PVHA **(D)**. Publications are sorted, in ascending order, by the year of publication and, for those with the same publication year, by alphabetical order. The *x* axis displays the resulting ordinal numbering (*ID* variable in the **Supplementary Material**). Labels on the *x* axis are placed on the first publication of the corresponding publication year.

assessing changes in vent locations due to spatial migration of volcanism in geological time (Jaquet et al., 2017).

Eruption Impacts

Mixed datasets are more commonly used than non-open datasets (**Figure 2A**). This may be due to an increased accessibility to databases of some key elements for the PVHA such as wind profiles for tephra fallout (Kalnay et al., 1996; Dee et al., 2011) or digital elevation models for mass flows (e.g., Shuttle Radar Topography Mission)[4]. Recent advances are linked with: (1) the comprehensive quantification of inter- and intra-eruption-size aleatory variability of quantities such as the mass eruption rate, erupted mass or volume, column height, column-collapse height, etc., (e.g., Biass et al., 2016; Sandri et al., 2016; Tierz et al., 2016b); and (2) the recognition and quantification of diverse sources of epistemic uncertainty, which significantly affect the PVHA (e.g., Stefanescu et al., 2012a,b; Spiller et al., 2014; Tierz et al., 2016a). The parallel development of detailed, yet relatively fast, physical models and versatile statistical models has aided the quantification of the aforementioned uncertainties. Some examples include open-access numerical codes for granular flows (TITAN2D, Patra et al., 2005; *LaharFlow*)[5] and uncertainty quantification techniques ranging from probabilistic graphical models (e.g., Sobradelo et al., 2014; Tonini et al., 2015; Tierz et al., 2017) to polynomial chaos methods (Dalbey et al., 2008; Tierz et al., 2018) and stochastic-process emulators (Bayarri et al., 2009; Spiller et al., 2014; Rutarindwa et al., 2019).

Integrated PVHA

According to the Sample, it has been the most common PVHA over the last years (**Figure 2D**) and it predominantly uses non-open data (**Figure 2A**). Notwithstanding, the range and scope of open-access databases for integrated PVHA seems to be increasing. Long-term programs like GVP have been

[4]https://www2.jpl.nasa.gov/srtm/

[5]https://www.laharflow.bristol.ac.uk/

joined by other efforts such as LaMEVE, FlowDat (Ogburn, 2012)[6], DomeHaz (Ogburn et al., 2015)[7], the Eruption Source Parameter database (Mastin et al., 2009)[8], the Catalog of Icelandic Volcanoes[9], etc. Recent advances have used some of these datasets to parameterize event trees in novel multi-volcano PVHA of tephra fallout (Jenkins et al., 2012) or PDCs (Sandri et al., 2018). Other advances, with potential applicability to integrated PVHA, have designed: (a) community cyberinfrastructure platforms that host or link to other open-access databases and provide online tools to support hazard assessment (Vhub, Palma et al., 2014; Volcanic Hazards Assessment Support System by G-EVER, Takarada, 2017)[10,11]; or (b) methods to identify objective sets of analogue volcanoes from global databases (VOLCANS, Tierz et al., 2019).

DISCUSSION

In my view, further and wider development of long-term PVHA is hindered by data scarcity as well as by some misconceptions and criticism toward PVHA itself.

Data Scarcity in PVHA

Volcanological data (**Figure 1**) are the best possible source of information to quantify aleatory uncertainty in volcanic hazard (e.g., Newhall and Hoblitt, 2002; Marzocchi and Bebbington, 2012; Connor et al., 2015; Pallister et al., 2019). Data discovery can alter this quantification by changing the experimental concept (Marzocchi and Jordan, 2014) and this is especially acute at the scale of individual volcanoes and for infrequent, large-size eruptions. For instance, for some decades, the Campi Flegrei caldera (Italy) was known to have undergone two caldera-forming eruptions, one at ∼39 ka (the Campanian Ignimbrite eruption; Fedele et al., 2003) and another at ∼15 ka (the Yellow Neapolitan Tuff eruption; Deino et al., 2004). Recently, new evidence for a third caldera-forming eruption at ∼29 ka (the Masseria del Monte Tuff eruption) has been found (Albert et al., 2019). This discovery has drastically reduced the expected repose interval for caldera-forming eruptions at Campi Flegrei.

It is also important to distinguish between lack of data discoverability (Loughlin et al., 2015) and lack of data accessibility (see **Definitions**). At present, a number of volcanological datasets, typically collected at specific volcanic systems (e.g., Cioni et al., 2008; Thompson et al., 2015; Bevilacqua et al., 2018), are stored in non-open-access publications and, hence, are not freely available to the entire volcanological community. Open-access publications are becoming more customary, which increases the availability of open data to perform PVHA (e.g., Sobradelo et al., 2011; Biass et al., 2014; Jenkins et al., 2019), but there is still an urgent need to discover, assemble, digitize and store volcanological data in open-access databases (e.g., Geyer and Marti, 2008; Ogburn, 2012; Ogburn et al., 2015, 2016b; Newhall et al., 2017) that help develop *Next-Generation* PVHA. International synergies, such as GVP, the Global Volcano Model[12], European Plate Observing System[13], European Open Science Cloud[14] or EarthCube[15], can play key roles in facilitating the generation and maintenance of such databases, as well as in the transition toward open science in general, for which not only open data but open models and workflows would also be required.

There are significant and varied challenges that play a role in the release of open data. For instance, individual researchers or institutions may be reluctant to release their data until fundamental research has been successfully conducted using those data. Hence, a *grace period* of a few years (e.g., 2 years in WOVOdat)[16] can provide the scope for initial interpretation and publication of results linked to the data. Other difficulties might be: economical and/or logistical (e.g., availability of long-term funding and tailored student supervision to help make existing data accessible), technological (e.g., software and hardware development) and/or legal and policy-related, ranging from intellectual property rights to protection of personal data. For instance, data-protection policies may be different across countries and/or change over time, within a given country or region (e.g., General Data Protection Regulation of May 2018 in Europe[17]). Particularly in volcanology, expert elicitation has become an important tool to extract data for PVHA (e.g., Aspinall, 2006; Selva et al., 2012a; Hincks et al., 2014; Thompson et al., 2015; Christophersen et al., 2018). The elicitation process has ethical and legal implications (e.g., Hemming et al., 2018), such as anonymity of the generated data, that need to be carefully considered while moving toward more open-data and open-science environments that facilitate PVHA worldwide.

Misconceptions Around PVHA

I focus here on three that I consider the most relevant. First, probabilistic approaches are sometimes criticized because of their overall complexity. However, it should be noted that PVHA is an expansion of deterministic approaches (Marzocchi and Bebbington, 2012). That is, a probabilistic hazard product can be converted into a "deterministic" one while the contrary does not hold. The versatility of PVHA should be an asset, not a detriment. For instance, a collection of hazard curves covering a spatial grid actually represents a set of probability and hazard maps that can be derived from the hazard curves by using thresholds in either the hazard-intensity measure (e.g., flow speed) or the probability of exceedance, respectively (e.g., Selva et al., 2014; Tonini et al., 2015; Tierz et al., 2018). The

[6]https://vhub.org/resources/2076
[7]https://vhub.org/resources/1742
[8]https://www.bgs.ac.uk/research/volcanoes/esp/search.cfc?method=viewHome
[9]http://icelandicvolcanos.is/
[10]https://vhub.org/
[11]http://volcano.g-ever1.org/
[12]https://globalvolcanomodel.org/
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[14]https://ec.europa.eu/research/openscience/index.cfm?pg=open-science-cloud
[15]https://earthcube.org
[16]https://wovodat.org/about/about.php
[17]https://ec.europa.eu/info/law/law-topic/data-protection/data-protection-eu_en

latter case is effectively equivalent to producing a scenario-based hazard map with known probability of exceedance. One key difference in deterministic, scenario-based hazard maps is that the associated probability of exceedance is not known (e.g., Esposti Ongaro et al., 2008; Charbonnier and Gertisser, 2012; Capra et al., 2015). Nevertheless, it is also important to acknowledge that probabilistic and deterministic approaches should not be seen as an "either-or choice" (e.g., Newhall and Pallister, 2015; Rouwet et al., 2017): both methods are reciprocally informative and beneficial for the goal of improving volcanic hazard assessments (e.g., Marzocchi et al., 2008; Marzocchi and Bebbington, 2012; Newhall and Pallister, 2015).

Secondly, validation of probabilistic hazard forecasts is necessary (Marzocchi and Bebbington, 2012; Marzocchi and Jordan, 2014; Connor et al., 2015) but not always there are enough data (**Figure 1**) available for such purpose (e.g., Marzocchi et al., 2004, 2008). In this context, a successful volcanic hazard assessment should be seen as one that efficiently delivers vital messages that help mitigation of volcanic risk (Pallister et al., 2019). Depending on the volcanological and socio-political context, the nature of this message can vary remarkably: from evidencing the possibility of far-reach PDCs during escalating phases of unrest (e.g., Mount Pinatubo, in June 1991: Newhall and Punongbayan, 1996; Newhall and Pallister, 2015) to raising awareness of the relevance of volcanic hazard at under-studied explosive volcanic systems with long repose intervals (e.g., Main Ethiopian Rift: Vye-Brown et al., 2016). In densely populated, heavily industrialized areas built on or surrounded by several volcanoes (e.g., the metropolitan area of Napoli, Italy, ∼3 M inhabitants), long-term PVHA represents a vital asset to deliver effective hazard-related messages. Considering Somma-Vesuvius and Campi Flegrei separately, long-term PDC hazard is most crucially controlled by different aspects at the two volcanoes. At Somma-Vesuvius, the size of the next eruption is a key factor controlling the volume and spatial reach of PDCs (Gurioli et al., 2010; Tierz et al., 2016a,b; Sandri et al., 2018) while vent-opening variability (Tadini et al., 2017) has a limited influence, partly due to major topographic controls on PDC propagation exerted by the stratocone and Mount Somma (Esposti Ongaro et al., 2008; Tierz et al., 2016a, 2018). At Campi Flegrei, eruption size has a more restricted effect on the volume and spatial reach of PDCs, for the most-likely explosive eruption sizes (Orsi et al., 2004, 2009; Neri et al., 2015; Tierz et al., 2016b). However, the location of the next eruptive vent (Selva et al., 2012b; Bevilacqua et al., 2015; Rivalta et al., 2019) has a paramount importance, given the complex intra-caldera topography and the smaller PDC invasion areas at Campi Flegrei (Tierz et al., 2016b; Bevilacqua et al., 2017; Sandri et al., 2018).

Finally, PVHA is often solely seen as an end product while it should also be considered a driver for research. If epistemic uncertainties are comprehensively quantified and ranked (e.g., Stefanescu et al., 2012a,b; Rougier and Beven, 2013; Spiller et al., 2014; Tierz et al., 2016a), then sensitivity of PVHA outputs can be explicitly explored (e.g., Tierz et al., 2016a; Bevilacqua et al., 2017; Sandri et al., 2018), and data collection can be aimed at reducing the overall uncertainty to improve volcanic hazard assessment (e.g., Tierz et al., 2016a; Trolese et al., 2019). The above example of PVHA of PDCs at the metropolitan area of Napoli exemplifies how research can focus on the most critical, volcano-specific aspects linked to PDC hazard: e.g., spatial probability of vent opening at Campi Flegrei and probability of eruption size at Somma-Vesuvius.

FUTURE DIRECTIONS

I propose four major steps to improve long-term PVHA in the context of an increased availability of open-access datasets:

1. *Unraveling the links between global and local frequency-magnitude distributions:* there is still debate about the portability of global frequency-magnitude distributions (Papale, 2018; Rougier et al., 2018) to regional (Sheldrake and Caricchi, 2017) and individual-volcano scales (Bebbington, 2014). Bayesian hierarchical models are a structured approach to accommodate end-member interpretations (Ogburn et al., 2016a) but different exchangeability assumptions between analogue volcanoes should be investigated to improve such models. Novel tools to identify objective sets of analogue volcanoes will facilitate such analyses (VOLCANS, Tierz et al., 2019);
2. *Toward the use of data-generating processes to model vent locations:* it would be preferable to use the data-generating process itself (i.e., magma transfer to the surface), instead of mostly focusing of past-vents data, to derive spatial PDFs of vent opening. Further developments in: (a) testing the spatial distributions of past vent locations against meaningful geological and geophysical data (Martin et al., 2004; Runge et al., 2016); and/or (b) applying hybrid physical-statistical approaches to simulate dike propagation trajectories and calculate spatial probabilities for future vent locations (Rivalta et al., 2019) are promising ways forward;
3. *Increased granularity in intra-eruption forecasting*: almost every PVHA of hazardous phenomena aggregates volcanic activity at the level of the single eruption (e.g., Jenkins et al., 2012; Becerril et al., 2014; Sandri et al., 2018) but very few incorporate the dynamic nature of intra-eruption phenomenology (e.g., Wolpert et al., 2018; Bebbington and Jenkins, 2019). More effort should be put in this direction and open-access, global datasets will be a fundamental resource for probabilistic models that incorporate this level of granularity in eruption dynamics (Cassidy et al., 2018);
4. *From hazard summation to hazard interaction in multi-hazard assessments at volcanoes:* the majority of volcanic multi-hazard assessments analyze hazardous phenomena separately and then combine or add their resulting hazard footprints (e.g., Sandri et al., 2014; Bartolini et al., 2015). There are very few examples where the hazard interaction is explicitly quantified (e.g., Volentik et al., 2009; Tierz et al., 2017). Probabilistic graphical

models (Koller and Friedman, 2009) can help quantify such critical interactions and their construction could strongly benefit from techniques such as machine learning (Anantrasirichai et al., 2019), if enough open volcanological data (**Figure 1**) were available.

The volcanological community has been able to enlarge its collective expertise over the last decades by engaging with scientists from diverse fields such as statistics, engineering or computer science. This has already resulted in major breakthroughs in long-term PVHA (e.g., Barberi et al., 1990; Wadge et al., 1994; Connor and Hill, 1995; Newhall and Hoblitt, 2002; Bayarri et al., 2009; Marzocchi et al., 2010; Jenkins et al., 2012; Bebbington, 2014, 2015; Jaquet et al., 2017; Tierz et al., 2017; Sandri et al., 2018). A vital next step relates to creating, expanding and maintaining more open-access volcanological datasets, as well as open-source software and workflows (e.g., data processing), that can support long-term PVHA worldwide.

DEFINITIONS

Open Data

Any type of data that any user can access and re-use, entirely free of charge, through a device equipped with an Internet connection (NB. Data in the GVP database is considered as open data, even prior to its release as an open-access database in 2002, Siebert and Simkin, 2002). Please note that *fully open data* would also imply free availability of the software and workflows used to generate these data. A simplified approach, where open data refers only to data used to compute long-term PVHA (see **Figure 1**), was taken here for the sake of facilitating the analysis shown in **Figure 2** and the Electronic **Supplementary Material**.

Non-open Data

Any type of data that does not comply with the definition given for open data. For example, all data found in subscription-based or pay-per-view articles is considered non-open. Please note that many authors may be willing to grant open access to their data upon publication. However, from the user point of view, data accessibility ultimately depends on the specific access policy associated with each published article.

Data Scarcity

General lack of data for any given volcano or group of volcanoes, independently of the reason behind this scarcity.

Data Discoverability

Quality of any kind of data for a given volcano or group of volcanoes of being able to be *discovered* through identification, description, measurement, sampling, etc.

Data Accessibility

Quality of any kind of data for a given volcano or group of volcanoes of being able to be accessed (and re-used) as open data. Please note that the concept of data accessibility may contain finer gradations (e.g., data in repositories, supplementary material files; maps drawn on an article; data available from author upon request, etc.), which would result in more data categories than the three distinguished in this manuscript: open, non-open and mixed. A simplified categorisation was chosen here for the sake of facilitating the analysis shown in **Figure 2** and the Electronic **Supplementary Material**.

Data Availability

Quality of any kind of data for a given volcano or group of volcanoes of being available for its re-use as open data. In the context of the manuscript, synonym of data accessibility.

AUTHOR'S NOTE

New data used in this study are shown in the figures presented and available in the **Supplementary Material**. Figures were generated using Inkscape software (Harrington, 2004–2005) and R programming language (R Core Team, 2013) and color schema were based on www.ColorBrewer.org (Brewer, 2018).

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

PT conceived this perspective, collected and processed the data, analyzed the results, generated the figures, wrote the manuscript, and approved all its versions.

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SUPPLEMENTARY MATERIAL

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