npj | natural hazards

Perspective

https://doi.org/10.1038/s44304-024-00033-8

From rest to eruption: How we should anticipate volcanic eruptions

J. Martí

Volcanic eruptions are typically preceded by unrest, marked by increased seismicity, ground deformation, and gas emissions. Unrest can last from decades to minutes. Accurate eruption forecasting relies on real-time monitoring and understanding the volcano's past behavior. Long-term hazard assessments, combined with real-time data, help identify probable eruptive scenarios (short-term hazard assessment), improving forecasting during volcanic crises.

Volcanic eruptions are among the most destructive natural hazards and may disrupt life and human socio-economic activities even at a global scale. To reduce the potential impacts of volcanic eruptions, it is crucial to be able to anticipate them well in advance. It is generally found that volcanic eruptions are preceded by changes in the behavior of the volcano (i.e., volcanic unrest), including an increase in seismicity, surface deformation, and gas emissions[1–10]. These signals may be recorded by various monitoring instruments and, in many cases, they may also be felt by the populations leaving close to the volcano.

Every volcano has its own physical and chemical characteristics (internal structure, rock rheology, magma composition, etc.), so pre-eruptive unrests may show significant variations for the monitored geophysical and geochemical parameters from one volcano to another. A given volcano may show similar values for given parameter (e.g., RSAM) when preparing for eruption of similar size and characteristics (e.g., Merapi[11]) but may also show unrest episodes that differ from those from previous eruptions[8,12]. The situation is even more complex in the case of volcanoes that have been dormant for long periods and have not erupted in historical times. We have no record of monitoring data to use as a background, and the detailed knowledge about previous eruptions may also be lacking (e.g., Sinabung volcano, 2010, Indonesia[13]).

Establishing potential patterns in the evolution of volcanic unrest that could help identifying the outcome within a limited degree of uncertainty, requires the analysis of as many unrest episodes as possible[14]. The importance of having large datasets to use probabilistic analysis or other approaches in eruption forecasting[15], stresses the need of a database of observational data freely available for being consulted. However, the available databases on volcanic unrest[8,12,16–19], as well as the datasets stored in each volcanic observatory around the world, require to be open and containing data stored in a comparable format, so existing data can be reported and interpreted in the same way (i.e., using same formats and time scales)[20] to be able to identify common or different behavior patterns among all volcano types and, thus, to establish effective methods to forecast volcanic eruptions.

However, eruption forecasting cannot be only based on the analysis of volcanic unrest. It also requires to identify which outcomes from such unrest (e.g.: no eruption, phreatic explosion, magmatic eruption) have the highest probabilities of occurrence and how they are associated with a given unrest pattern. This is necessary to implement the emergency plans according to the most probable outcomes. Therefore, eruption forecast also requires a hazard assessment that needs to be combined with the unrest analysis, in order to get a precise short-term hazard analysis that could identify how, when and where the next eruption will be, rather than only knowing whether the eruption will occur or not[21,22]. Otherwise, it may result in failed eruption forecasts either because eruption does not occur or because it does not correspond with the expected size (e.g.: La Sufriere Guadeloupe, 1976; Akutan, Alaska, 1996; Tungurahua, Ecuador, 1999; Paricutin, Mexico, 2006; Fourpeaked, Alaska, 2006; Mayon, Philippines, 2018).

Here I comment on some aspects related to how volcanic eruptions can be anticipated. I discuss the need to conduct long-term hazard assessment in addition to volcano monitoring, to be able to provide more robust eruption forecasting during volcanic crises. In this sense, I propose that a systematic integration of a detailed knowledge of the eruptive history of a volcano, based on the analysis of the geological (and historical) records, and monitoring data on its current state of activity, is the main way to forecast future eruptions.

Volcanic unrest

A volcanic eruption typically requires an overpressurised batch of magma to ascent to the earth surface or, conversely, decompression of the shallow magma systems due to mass unloading (e.g.: sector collapse) of the volcanic edifice, or rupture of the magma chamber caused by tectonics (e.g., earthquake). Magma may come from shallow or deep reservoirs (or chambers) where it has accumulated and differentiated, or even directly from the source region[23]. To reach the earth's surface, magma needs to deform the surrounding rock, displacing it apart and opening new fractures, to create the necessary space and pathways to cross from deeper to shallower levels[24,25]. This will produce a series of changes in the vicinity of the magma that may be translated into surface deformation, seismicity, or other changes of potential fields that should be detected by ground based and remote geophysical monitoring systems[1,2]. Moreover, when magma approaches to the surface

Natural Risks Assessment and Management Service (NRAMS), Department of Geosciences, IDAEA-CSIC, Barcelona, Spain. e-mail: j.marti@csic.es

and pressure decreases, the dissolved gases may exsolve and separate from the liquid phase, thus giving rise to appearance of geochemical indicators of magma ascent[26–28].

However, a volcano may also change its state due to external factors not related to magma movement, such as changes in regional tectonics[29] or in the conditions of the associated geothermal systems[26,27,30], which will also result in a variation of the monitored parameters. Whether or not the observed activity at a given volcano is caused by changes in the magmatic system or by changes of the regional stress field or the geothermal system, and whether or not the unrest phase will end with an eruption, is the challenging question that needs to be answered with interpretation of monitoring data and good knowledge of the past behavior of the volcano[5,8].

An increase of activity (seismicity, ground deformation, gas emissions) compared with a previous background level is what is generally known as volcanic unrest[12] (Fig. 1). The background level of activity above which we may consider that volcanic unrest is occurring, needs to be defined for each volcano by experts who know about its present and past behavior. Establishing a background level of activity should be mainly based on the information provided by the monitoring networks, but also considering other volcanological aspects such as the past history of the volcano and historical chronicles. Comparison between volcanoes may sometimes help[25,31], but volcanoes are complex natural systems, subjected to a large number of non-linear processes that make them easily depart from pre-assumed patterns. Even if eruptions of similar characteristics may occur at different volcanoes it is not necessarily true that unrest episodes preceding them have to be also similar (e.g., El Hierro 2011–2012 and La Palma 2021 eruptions in the Canary Islands). When establishing the background level for a particular volcano, it is important to keep in mind that the range of variation of monitoring parameters, as well as the time scales for these variations, may differ significantly from one volcano to another or even at the same volcano from one eruption to another[32]. So, establishing comparisons between volcanoes or even assuming the same degree of background activity for different volcanoes, even if they are similar in composition or behavior, is not a good solution. It is essential to thoroughly understand the specific volcano before determining its range of activity.

The analysis of an unrest episode requires defining its time limits (when it starts and when it finishes) (Fig. 1). In some cases, the background level of activity may be not known because of lack of monitoring or the short time in which it has been operating. In such cases, the geological history of the volcano and historical records, when they exist, are the main tools to forecast future activity. In others, we may observe fluctuations (i.e., increases and decreases of activity) (e.g., Campi Flegrei caldera[33]) that may not help to define a clear tendency in the evolution of the unrest. Also, there are volcanic systems in permanent unrest since monitoring was implemented, so there is no confidence to establish a reference background level[34]. Moreover, in retrospective analysis, it would be interesting to consider time scales much longer than the monitored period or the unrest phenomena described in historical chronicles, but volcanic unrest is not registered in the geological records. Or, we may face the dilemma of whether or not significant increases of activity not ending with an eruption can be considered as unrest (Fig. 2).

Any unrest episode will have different stages and forecasting possible outcomes should be more reliable as time passes and more information is gathered. Figure 3 shows a flow chart-type diagram detailing the sequential way in which we could approach the different steps of a volcanic unrest analysis. First, it is necessary to characterize the volcanic system in terms of eruption dynamics, eruption frequency, and magma composition. In addition, we need to gather information on the geodynamic setting and degree of deformation (seismicity, strain, etc.) that the volcanoes may be currently experiencing at a regional or local level. This allows discriminating between local deformation that may be attributed to the volcano from that related to the activity of plate boundaries or mantle instabilities (e.g., mantle plume upwelling). Another important step is to identify groups of unrest indicators that will better describe the evolution of unrest in a volcano[8]. These will surely include seismicity, surface deformation, potential fields, gases, and may be other that we could consider in each particular case and depending on monitoring facilities available[35]. For example, in open vent volcanoes degassing and seismicity seem to be better indicators of unrest[36] than deformation, whereas currently, the dome complex of Laguna del Maule is experiencing a huge deformation and significant seismicity, although limited or no degassing[37]. The next step is to specify which particular parameters we will consider (e.g.: for seismicity: seismic energy released, total number of VT events, presence of LP events, etc.; for gases: total gas flux, presence of SO_2, etc.), and which ranges of variation may be assumed to consider a change in activity significant or representative of the evolution of the volcanic unrest[18].

Furthermore, to enhance our understanding of the volcanic system's behavior, it is essential to gather monitoring data during any eventual eruptions. This will reflect possible variations of monitoring parameters related to variations in eruption dynamics, which could indicate variations in the plumbing system. This analysis needs to be complemented with the

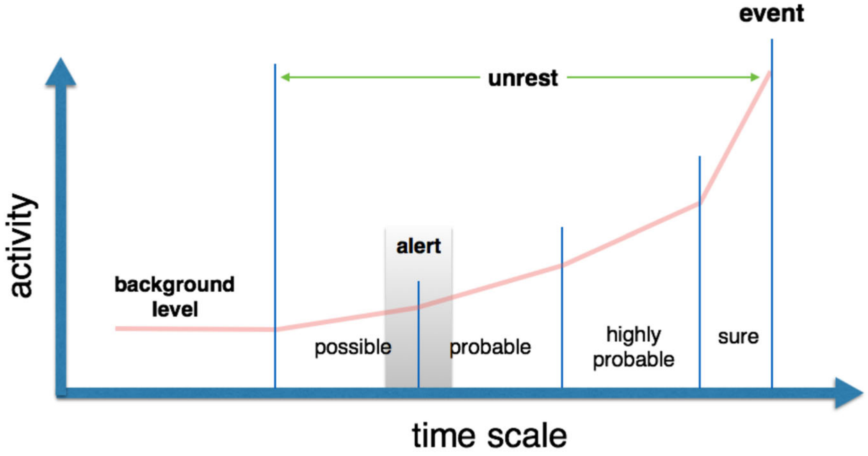

Fig. 1 | Time evolution of volcanic activity during an unrest episode (not to scale). Volcanic unrest starts when there is an increase of activity (i.e., increase in the values of the monitored parameters) in the volcanic system with respect to a previous background level. In most cases (e.g.: www.WOVOdat.org) volcanic activity will increase progressively, with a clear acceleration at the last moment, until an event occurs. This may be an eruption, a phreatic explosion, or also a sudden decrease of activity due to the relaxation of the system (e.g., due to massive degassing), returning to its normal state without any eruption or explosion. The occurrence of an event marks the end (the outcome) of that particular unrest, even if volcanic activity increases again (new unrest episode). The relative stages in the evolution of the unrest using probabilistic terms to indicate how it may are also indicated, as well as the time window in which usually an alert should declared. Despite the shape of the curve represented here is similar in most volcanic unrests, the exact level of activity and duration of the unrest may be significantly different between volcanoes and between eruptions of the same volcano.

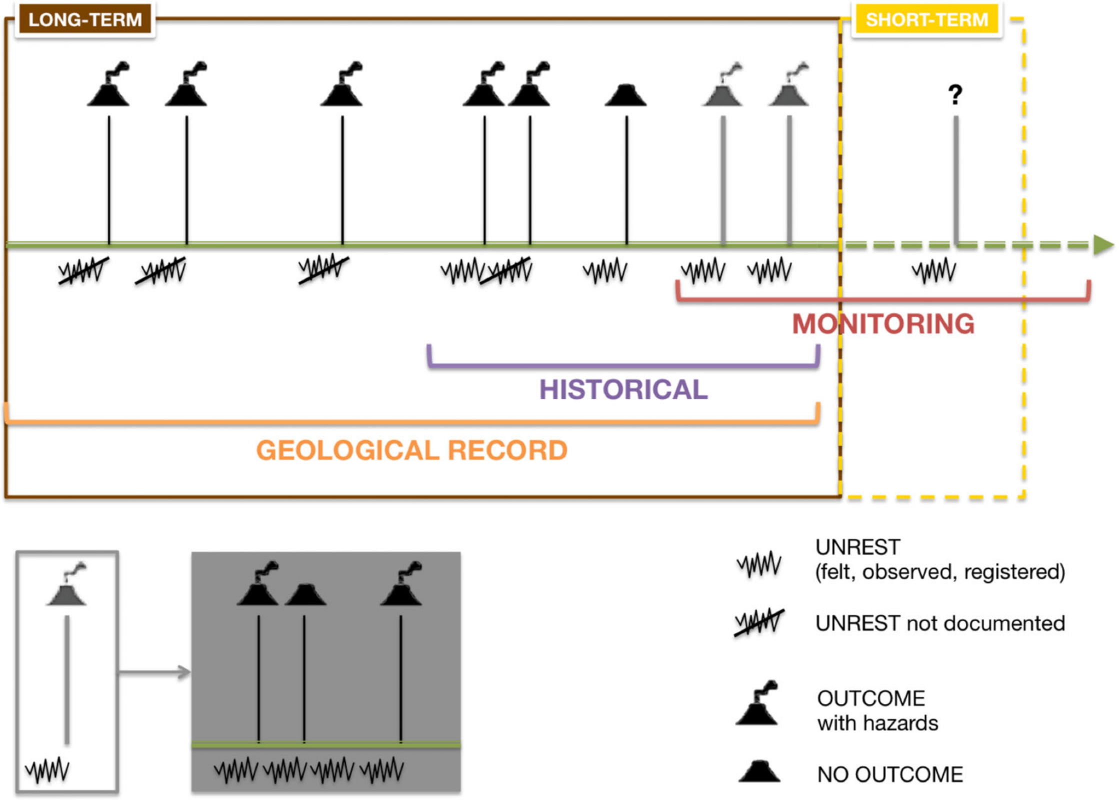

Fig. 2 | Time scale evolution of long- and short-term hazard analyses and variation of the degree of detail, considered in eruption forecast. Long-term hazard assessment: long-term assessment is based on historical and geological data, as well as on simulation models of possible hazards, and refers to the available time window before an unrest episode occurs in a volcanic system that currently shows no signs of unrest. Short-term hazard assessment: refers to the unrest phase, when complementary information resulting from the combination of long-term analysis and real-time monitoring data is used to update the status of the volcanic hazard and to forecast a possible eruption. Unrest: any variation with respect to the background level or, in other words, any change in the state or dynamics of the volcanic system, recorded by monitoring networks and/or perceived by the nearby populations, which correlates with a volcanic event (outcome in the terms of hazard), being this an eruption or no eruption. In the case that the unrest does not end up with an eruption, the return of the geophysical and geochemical indicators to a background level will coincide with the end of the unrest episode. Outcome: end of the unrest associated with a hazard occurrence. No outcome: end of unrest without associated hazard. Historical: time period that goes from the appearance of written records to present. Monitoring: time period that covers the registered instrumentally volcanic activity. Geological record: time period that covers all geological registers from a specific volcano or volcanic system.

petrological and rheological characterization of erupted products in near real time, as variations in their composition and physical properties may explain the changes observed in the monitoring signals[38,39]. Such systematization of unrest indicators, and combination with other geological data, should contribute to better understanding the physical meaning of the various levels of unrest, thus improving volcano forecasting.

Eruption forecasting, long- and short-term hazard assessments

In general terms, forecasting is defined as the process of making predictions of the future based on past and present data and analysis of trends[40,41]. In volcanology, forecasting basically intends to predict the occurrence of future eruptions (in space and time) based mainly on the analysis of unrest episodes[2,21,24,35,42–46]. This means that eruption forecasting concentrates on using real-time monitoring data to determine whether or not an eruption will occur, and if so, when it will happen. However, such forecasting is incomplete if we are not able to anticipate the kind of eruption and its potential extend (size) and impacts, for which it is necessary to also consider the past history of the volcano[22,47]. This task may be achieved by combining long-term hazard assessment with volcano monitoring, thus obtaining the short-term assessment and, finally, the eruption forecast[15,21].

Long-term hazard assessment is based on historical and geological data, and refers to how the volcano has behaved in the past, before a new unrest episode occurs[21,47–51]. In this case, fundamental geology is essential to establish reliable basis on which to build the hazard assessment structure, to determine the time constraints of the volcanic processes and eruption frequencies, and to characterize the products (i.e., hazards) from past eruptions[47]. Based on this information, long-term hazard assessment should identify all possible eruptive scenarios that have occurred in the past and, from them, the most probable that may occur in the future (Fig. 4). Long-term hazard assessment is essential for territorial planning and elaboration of emergency plans, as well as to implement educational programs addressed to inform general public on volcanic hazards.

Long-term volcanic hazard assessment is an essential part of any volcanic risk reduction program[47]. It can be considered as a sequential process aimed at implementing several actions necessary to determine the level of hazard of a particular area and, therefore, to contribute to reduce its potential impact. These actions include spatial analysis, temporal analysis, simulation of the eruptive scenarios, and elaboration of partial and total hazard maps. At each step it corresponds a variety of input data, such as historical, geographical, and geological data, theoretical models, and multiple outputs (Fig. 4). The results are highly dependent on the data used, and thus the completeness and quality of data sources is crucial for a proper long-term hazard evaluation. The spatial analysis consists on identifying from where past eruptions have been sourced and, consequently, will help to infer "where" the next eruption can take place, i.e., the spatial probability of occurrence of a new eruptive vent (volcanic susceptibility[52]). This analysis needs to be completed with the temporal probability, which informs on when past eruptions have occurred and on which scenarios characterize each past eruption. The temporal analysis consists of identifying all the possible eruptions recorded in the historical and geological records of the

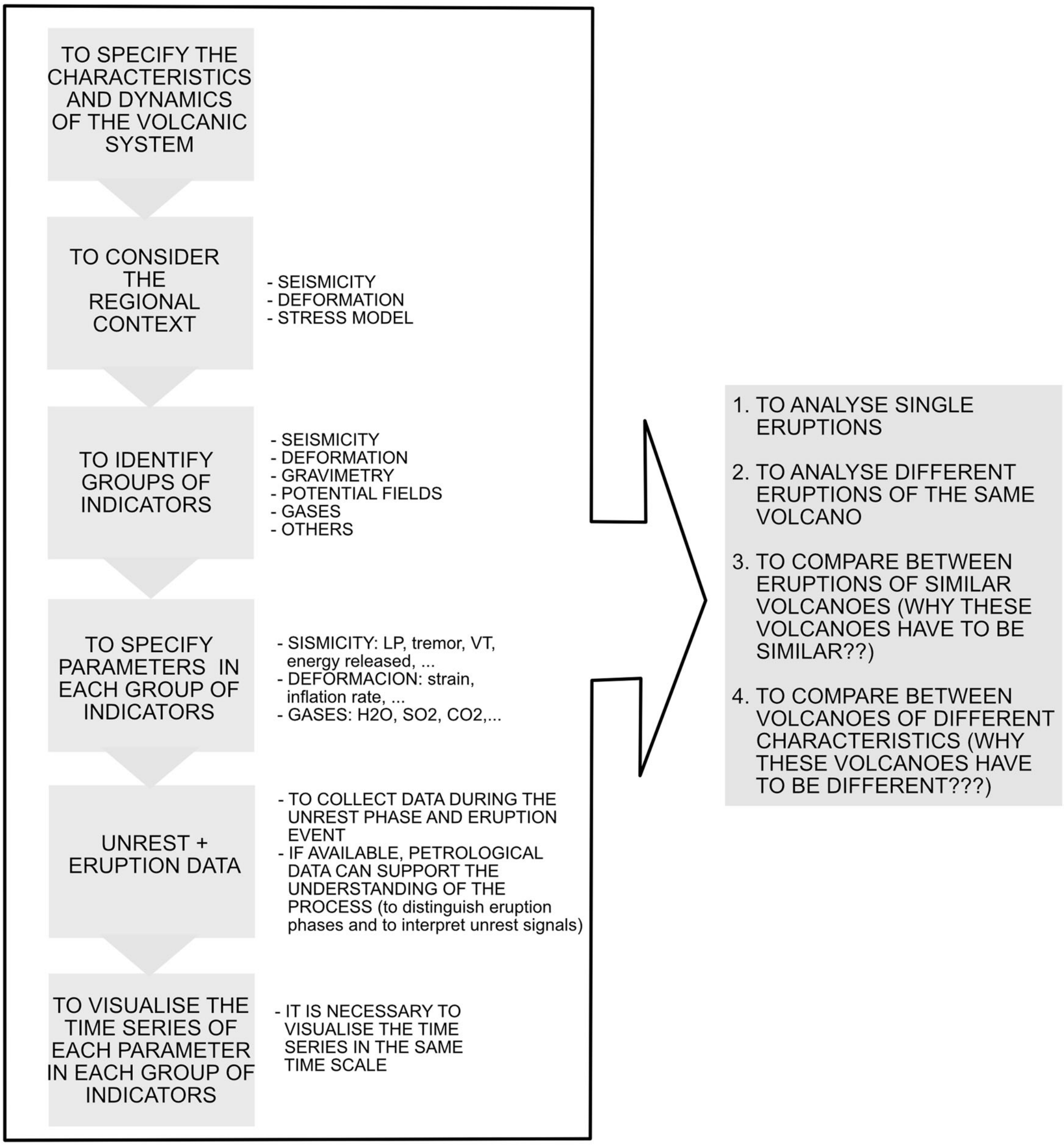

Fig. 3 | Volcanic unrest analysis. Schematic representation of the stages included in the volcanic unrest analysis, indicating the different aspects or parameters to be considered, and the possible uses of such analysis (see text for more explanation).

volcano and establishing, from this information, its eruptive recurrence, with which we can answer the question of "when" the new eruption will be. Complementing the information obtained from the temporal analysis, we have to proceed with the identification of all possible eruption scenarios occurred in the past and, from all them, which have occurred with a higher frequency (i.e., the most probable scenarios), and their potential characteristics and extend. This requires simulations to reproduce the possible eruptive scenarios and identifying the areas that may be affected by each of them. The last step in the long-term assessment is the elaboration of partial (for each hazard in particular or combinations of some of them) and total (considering all potential hazards) maps[47]. All the results from the long-term hazard assessment are expressed in probabilities, which implies the use of different methodologies (event trees, Bayesian Inference, Belief networks, expert assessment, etc.) to assign them, but I am not going to explain them here since it exceeds the purpose of this Perspective Contribution (see refs. 15,49–55)

During a volcanic unrest, such information will constitute the basis to identify the most probable outcome by conducting a short-term hazard assessment (Fig. 5). This combines the long-term analysis and real-time monitoring data to update the status of the volcanic hazard[15,21,32,48,53]. Short-term evaluation will constraint how, where and when the eruption will take place, although a considerable degree of uncertainty may still remain depending on how well we know our volcanic system[56–58]. Short-term hazard assessment (Fig. 5) permits to update the previous susceptibility map, to infer the most probably outcome (e.g.: eruptive scenarios) of the unrest phase, and, consequently, to identify the exposed elements and the actions to be undertaken to protect them. Therefore, results from the short-term analysis will be addressed to refine the emergency preparedness and to respond in the most effective way to the event.

Discussion and conclusions

The best way to reduce volcanic risk is by anticipating to volcanic eruptions. This may be achieved by undertaking a series of actions both in the long term, when the volcano is not showing signs of activity above its characteristic background level, and in the short term, when the volcano enters into a new unrest period. Among others, these actions should include hazard

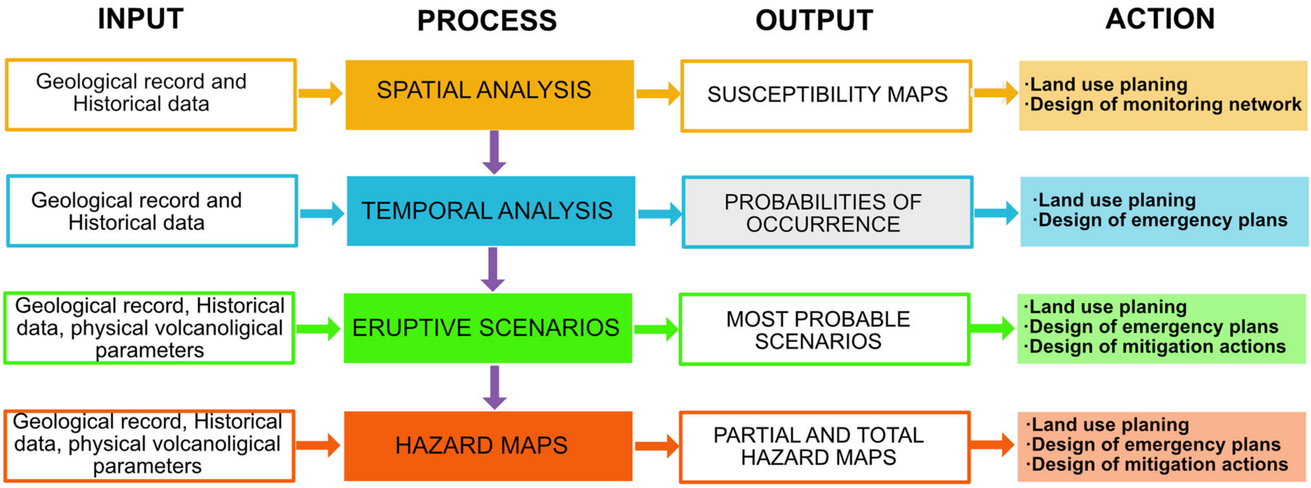

Fig. 4 | Long-term hazard assessment. Schematic representation of the sequential steps included in long-term hazard assessment, indicating the input parameters, possible outputs of each phase of such analysis, and the corresponding actions (see text for more explanation).

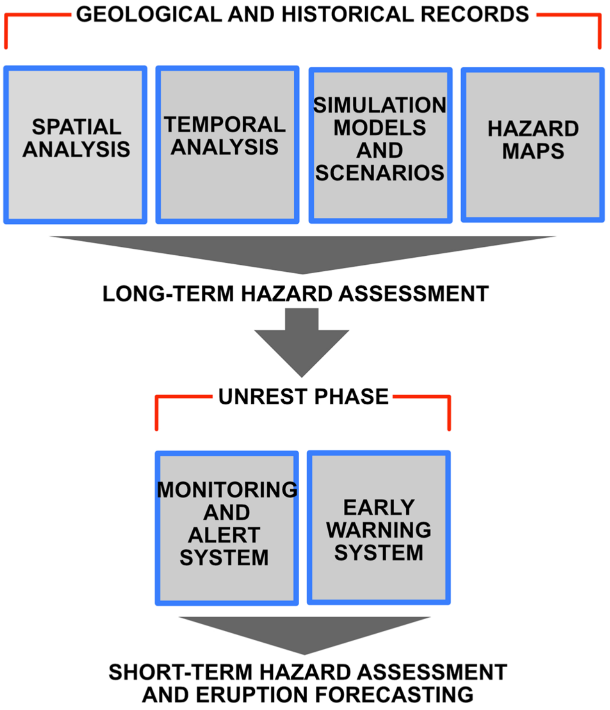

Fig. 5 | Eruption forecasting steps. Schematic representation of actions to be undertaken as a function of the time available (see text for more explanation).

assessment, implementation of monitoring systems, effective land planning, development and implementation of emergency plans, promoting educational programs, and implementing mitigation measures to reduce vulnerability. From the scientific side, hazard assessment and volcano monitoring are the most important contributions to reduce volcanic risk, together with educational actions addressed to improve population knowledge on volcanic hazards.

When a volcano enters into a state of anomalous activity or unrest, monitoring data should provide the necessary information to infer the causes of such unrest and its potential evolution. The evolution of an unrest episode will depend on the causes of the unrest (magmatic, tectonic, or geothermal), which may give different outcomes (magmatic eruption, phreatic explosion, sector failure, or others) in a range of locations with different possible eruption magnitudes, products, scope, etc.[32,50]. Each particular scenario is expected to result from a particular pattern in precursory activity. However, there are factors in each scenario that cannot be anticipated merely by studying monitoring data but which can be identified by examining the past eruptive history of the volcano. In an ideal situation, the short-term hazard assessment should be constructed on the long-term assessment, so knowing well the past eruption history of the volcano. However, when this is not known and an unrest starts, the short-term has to rely on an incomplete knowledge of the volcano and/or on comparisons with other potentially similar volcanoes. A good example of this situation was El Hierro eruption in 2011–2012, in the Canary Islands. In the case of El Hierro, no previous hazard assessment existed, so the most probable scenario, a submarine eruption, as it was shown by a subsequent study[59], was not anticipated. Consequently, scientific advisors and decision-makers considered possible eruptive scenarios that had much lower probabilities of occurrence, which implied making decisions with a higher cost than necessary[54].

The tremendous scientific and technological advance experienced by volcanology in recent years has resulted in the deterministic forecast of the eruptive behavior of volcanoes with a high eruption frequency and a good knowledge of their eruptive past, as is the case of the Stromboli volcanoes[60–65] and also of some more infrequent eruptions[24,66]. Moreover, the 2021 Fagradalsfjall eruption, Iceland, is a good example on how application of short-term eruption forecasting based on a previous long-term hazard assessment may provide accurate predictions (about 90% of coincidence in this case) even in places of long eruption recurrences (about 800 years since last eruption)[67].

However, despite these advances, real-time analysis of pre-eruptive activity in many volcanoes still cannot provide exact numbers (threshold values) to precisely predict when an eruption will begin. In fact, we are still far from acquiring the necessary amount of observational data able to guarantee the efficient application of statistical methods capable to identify discriminating patterns in the pre-eruptive behavior of volcanoes[21]. The fact that all volcanic systems, even those theoretically pertaining to the same volcano type, present different characteristics for what concerns internal structure, plumbing system, state of strain and stress, or magma rheology, does not facilitate the use of specific values as markers or thresholds that may be applied to forecast the future of a volcano. However, comparison between volcanic unrests among different volcanoes has occasionally provided, for example, coincidence in the total accumulated seismic energy values reached before eruptions[68], but in the same way these values have been clearly exceeded by orders of magnitude in other unrest episodes without leaving to an eruption[69].

Fortunately, the amount of available information is progressively increasing with the deployment and implementation of new monitoring networks, organization of new volcano observatories, and the development of new research on volcanic eruptions. Initiatives such as WOVOdat[19], complemented with other databases (Smithsonian GVP[17]; LAMEVE[70]; VOGRIPA, https://www2.bgs.ac.uk/vogripa/; DomeHaz[71]; CCCB[72]; Volcanic Unrest[12]; VUI[18]; VOLCANS[31], etc.), containing information on different aspects of volcanic phenomena (volcanoes, unrest, large eruptions, calderas, domes, etc.), should be welcome and fully supported, as they offer good data sources to identify pre-eruptive and eruptive behaviors among different volcanoes. However, the existing data are still too disperse, stored in a wide variety of formats and not always available. Fixing this gap requires an open collaboration between all scientists and the definition of common formats and agreement in their use in order to ensure that available data are compatible and comparable.

With this contribution, I only pretend to offer a systematic approach to what should be done to forecast future eruptions, by combining long-term hazard assessment (i.e., the geological and historical records of the volcano) with real-time monitoring data. To identify unrest patterns at the same volcano and from volcanoes with similar characteristics, it is crucial to obtain as many retrospective analyses as possible. This would help to categorize volcanoes according to unrest types or levels of unrest. Moreover, it would facilitate establishing predictive models based on the identification of patterns that repeated in the past and that may represent a particular relationship between unrest evolution, magma and rock properties, and potential eruption dynamics. In a similar way, the study of the past eruptive history of volcanoes will provide the clues to define their future potential hazard level. And is the combination of both, long-term hazard assessment and real-time monitoring, which will result in the most accurate forecasting for future eruptions.

Data availability

No datasets were generated or analyzed during the current study.

Received: 18 April 2024; Accepted: 23 October 2024;

References

1. Scarpa, R & Tilling, R.I. (eds) *Monitoring and Mitigation of Volcano Hazards* p. 841 (Springer-Verlag, Berlin Heidelberg, 1996).
2. Sparks, R. S. J. Forecasting volcanic eruptions. *Earth Planet. Sci. Lett.* **201**, 1–15 (2003).
3. Sandri, L., Marzocchi, W. & Zaccarelli, L. A new perspective in identifying the precursory patterns of eruptions. *Bull. Volcanol.* **66**, 263–275 (2004).
4. Cañon-Tapia, E. Volcanic eruption triggers: a hierarchical classification. *Earth Sci. Rev.* **129**, 100–119 (2014).
5. Rouwet, D. et al. Recognizing and tracking volcanic hazards related to non-magmatic unrest: a review. *J. Appl. Volcanol.* **3**, 17 (2014).
6. Stix, J. Understanding fast and slow unrest at volcanoes and implications for eruption forecasting. *Front. Earth Sci.* **6**, 56 (2018).
7. Illsley-Kemp, F. Volcanic unrest at Taupo volcano in 2019: causes, mechanisms and implications. *Geochem. Geophys. Geosys.* **22**, e2021GC009803 (2021).
8. Pritchard, M. E., Mather, T. A., McNutt, S. R., Delgado, F. J. & Reath K. Thoughts on the criteria to determine the origin of volcanic unrest as magmatic or non-magmatic. *Philos. Trans. R. Soc*. A 37720180008 https://doi.org/10.1098/rsta.2018.0008 (2019).
9. Gottsmann, J., Komorowski, J. C. & Barclay, J. Volcanic unrest and pre-eruptive processes: a hazard and risk perspective. in *Volcanic Unrest: From Science to Society, Advances in Volcanology, IAVCEI* (eds Gottsmann, J. et al.) 1–20 (Springer Open, Berlin, 2019).
10. Girona, T., Realmuto, V. & Lundgren, P. Large-scale thermal unrest of volcanoes for years prior to eruption. *Nat. Geosci.* **14**, 238–241 (2021).
11. Ratdomopurbo, A. et al. Overview of the 2006 eruption of Mt. Merapi. *J. Volcanol. Geotherm. Res*. https://doi.org/10.1016/j.jvolgeores.2013.03.019 (2013).
12. Phillipson, G., Sobradelo, R. & Gottsmann, J. Global volcanic unrest in the 21st century: an analysis of the first decade. *J. Volcanol. Geotherm. Res.* **264**, 183–196 (2013).
13. Gunawan, H. et al. Overview of the eruptions of Sinabung Volcano, 2010 and 2013–present and details of the 2013 phreatomagmatic phase. *J. Volcanol. Geotherm. Res.* **382**, 103–119 (2019).
14. Ardid, A. et al. Generalized eruption forecasting models using machine learning trained on seismic data from 24 volcanoes. Preprint at *Research Square* https://doi.org/10.21203/rs.3.rs-3483573/v1 (2023).
15. Whitehead, M. G. & Bebbington, M. S. Method selection in short-term eruption forecasting. *J. Volcanol. Geotherm. Res.* **419**, 107386 (2021).
16. Venezky, D. Y. & Newhall, C. G. *WOVOdat Design Document: The Schema, Table Descriptions, and Create Table Statements for the Database of Worldwide Volcanic Unrest (WOVOdat Version 1.0)* (USGS Openfile Report 2007-1117, 2007).
17. Siebert, L., Simbking, T. & Kimberly, P. *Volcanoes of the World* 3rd edn (Smithsonian Institution, University of California Press, 2010).
18. Potter, S. H., Scott, B. J., Jolly, G. E., Neall, V. E. & Johnston, D. M. Introducing the Volcanic Unrest Index (VUI): a tool to quantify and communicate the intensity of volcanic unrest. *Bull. Volcanol*. https://doi.org/10.1007/s00445-015-0957-4 (2015).
19. Costa, F. et al. WOVOdat – the global volcano unrest database aimed at improving eruption forecasts. *Dis. Prev. Manag.* **28**, 738–751 (2019).
20. Tomlinson, R. F. & Union géographique internationale. Global Database Planning Project. *Building Databases for Global Science* (ed. Mounsey, H.) (Taylor & Francis, London, 1988).
21. Poland, M. P. & Anderson, K. R. Partly cloudy with a chance of lava flows: forecasting volcanic eruptions in the twenty-first century. *J. Geophys. Res. Solid Earth* **125**, e2018JB016974 (2020).
22. Colosi, P. & Brodsky, E. E. How big will the next eruption be? *J. Appl. Volcanol.* **11**, 4 (2022).
23. Becerril, L. et al. Depth of origin of magma in eruptions. *Sci. Rep.* **3**, 2762 (2013).
24. Kilburn, C. R. J. Forecasting volcanic eruptions: beyond the failure forecast method. *Front. Earth Sci.* **6**, 133 (2018).
25. Kilburn, C., Kilburn, R. J. & Bell, A. F. Forecasting eruptions from long-quiescent volcanoes. *Bull. Volcanol.* **84**, 25 (2022).
26. Chiodini, G. et al. Geochemical indicators of possible ongoing volcanic unrest at Nisyros Island (Greece), *Geophys. Res. Lett*. **29** https://doi.org/10.1029/2001GL014355 (2002).
27. Chiodini, G. Magmas near the critical degassing pressure drive volcanic unrest towards a critical state. *Nat. Commun.* **7**, 13712 (2016).
28. Aiuppa, A. et al. Forecasting Etna eruptions by real-time observation of volcanic gas composition. *Geology* **35**, 1115–1118 (2007).
29. Hill, D. P., Pollitz, F. & Newhall, C. Earthquake-volcano interactions. *Phys. Today* **55**, 41 (2002).
30. Gaeta, F. S. et al. Genesis and evolution of unrest episodes at Campi Flegrei caldera: the role of thermal fluid-dynamical processes in the geothermal system. *J. Geophys. Res.* **103**, 20921–20933 (1998).
31. Tierz, P., Loughlin, S. C. & Calder, E. S. VOLCANS: an objective, structured and reproducible method for identifying sets of analogue volcanoes. *Bull. Volcanol.* **81**, 76 (2019).
32. Sobradelo, R. & Martí, J. Short-term volcanic hazard assessment through Bayesian inference: retrospective application to the Pinatubo 1991 volcanic crisis. *J. Volcanol. Geotherm. Res.* **290**, 1–11 (2015).

33. Del Gaudio, C., Aquino, I., Ricciardi, G. P., Ricco, C. & Scandone, R. Unrest episodes at Campi Flegrei: a reconstruction of vertical ground movements during 1905–2009. *J. Volcanol. Geotherm. Res.* **195**, 48–56 (2010).
34. Roman, D. C. et al. Mechanisms of unrest and eruption at persistently restless volcanoes: insights from the 2015 eruption of Telica Volcano, Nicaragua. *Geochem. Geophys. Geosys.* **20**, 4162–4183 (2019).
35. Acocella, V. et al. Towards scientific forecasting of magmatic eruptions. *Nat. Rev. Earth Environ.* **5**, 5–22 (2024).
36. Laiolo, M. et al. Shallow magma dynamics at open-vent volcanoes tracked by coupled thermal and SO_2 observations. *Earth Planet. Sci. Lett.* **594**, 117726 (2022).
37. Le Mével, H., Cordova, L., Cardona, C. & Feigl, K. Unrest at the Laguna del Maule volcanic field 2005–2020: renewed acceleration of deformation. *Bull. Volcanol*. **83** https://doi.org/10.1007/s00445-021-01457-0 (2021).
38. Saunders, K., Blundy, J., Dohmen, R. & Cashman, K. Linking petrology and seismology at an active volcano. *Science* **336**, 1023–1027 (2012).
39. Martí, J. et al. Correlation of magma evolution and geophysical monitoring at El Hierro (Canary Islands) 2011–2012 submarine eruption. *J. Petrol*. https://doi.org/10.1093/petrology/egt014 (2013).
40. Makridakis, S., Wheelwright, S., Hyndman, R. & Chang, Y. *Forecasting Methods and Applications* 3rd edn (Wiley, New York, 1998).
41. Hyndman, R. J. & Athanasopoulos, G. *Forecasting: Principles and Practice* (O-Text – Online Open Access Text Books, 2013).
42. Decker, R. W. Forecasting volcanic eruptions. *Ann. Rev. Earth Planet. Sci.* **14**, 267–291 (1986).
43. Voight, B. A method for prediction of volcanic eruptions. *Nature* **332**, 125–130 (1988).
44. Chouet, B. Long-period volcano seismicity: its sources and use in eruption forecasting. *Nature* **380**, 309–316 (1996).
45. McNutt, S. Seismic monitoring and eruption forecasting of volcanoes: a review of the state of the art and case studies. in *Monitoring and Mitigation of Volcano Hazards* (eds Scarpa, R. & Tilling, R. I.) 99–146 (Springer-Verlag, Berlin Heidelberg, 1996).
46. Smith, R. & Kilburn, C. R. J. Forecasting eruptions after long repose intervals from accelerating rates of rock fracture: the June 1991 eruption of Mount Pinatubo, Philippines. *J. Volcanol. Geotherm. Res.* **191**, 129–136 (2010).
47. Martí, J. *Assessing Volcanic Hazard: A Review*. Oxford Handbooks Online. Retrieved May 25, 2019, from https://www.oxfordhandbooks.com/view/10.1093/oxfordhb/ 9780190699420.001.0001/oxfordhb-9780190699420-e-32 (2017).
48. Blong R. Volcanic hazards and risk management. in *Encyclopedia of Volcanoes* (eds Sigurdsson, H. et al.) 1215–1227 (Academic, San Diego, 2000).
49. Marzocchi, W., Sandri, L. & Selva, J. BET_VH: a probabilistic tool for long-term volcanic hazard assessment. *Bull. Volcanol.* **72**, 705–716 (2010).
50. Sobradelo, R. & Martí, J. Bayesian event tree for long-term volcanic hazard assessment: application to Teide-Pico Viejo stratovolcanoes, Tenerife, Canary Islands. *J. Geophys. Res.* **115** https://doi.org/10.1029/2009JB006566 (2010).
51. Bartolini, S., Martí, J., Sobradelo, R. & Becerril, L. Probabilistic e-tools for hazard assessment and risk management. in *"Observing the Volcano World: Volcano Crisis Communication" Advances in Volcanology* (eds Fearnley, C. J. et al.) 571–583 https://doi.org/10.1007/11157_2017_15 (Springer, 2017).
52. Martí, J. & Felpeto, A. Methodology for the computation of volcanic susceptibility: an example for mafic and felsic eruptions on Tenerife (Canary Islands). *J. Volcanol. Geotherm. Res.* **195**, 69–77 (2010).
53. Marzocchi, W., Sandri, L. & Selva, J. BET_EF: a probabilistic tool for long- and short-term eruption forecasting. *Bull. Volcanol.* **70**, 623–632 (2008).
54. Sobradelo, R., Martí, J., Kilburn, C. & López, C. Probabilistic approach to decision-making under uncertainty during volcanic crises: retrospective application to the El Hierro (Spain) 2011 volcanic crisis. *Nat. Hazards* **76**, 979–998 (2015).
55. Selva, J. et al. Operational short-term volcanic hazard analysis: methods and perspectives. in *Volcanic Hazards, Risks and Disasters* (eds Papale, P. & Shroder, J. F.) 233–259 (Elsevier, Amsterdam, 2014).
56. Marzocchi, W., Newhall, C. G. & Woo, G. The scientific management of volcanic crises. *J. Volcanol. Geotherm. Res.* **247–248**, 181–189 (2012).
57. Martí, J. Scientific communication of uncertainty during volcanic emergencies. in *Global Volcanic Hazards and Risk* (eds Loughlin, S. et al.) 371–378 https://doi.org/10.1017/CBO9781316276273 (Cambridge University Press, Cambridge, 2015).
58. Sobradelo, R. & Martí, J. Using statistics to quantify and communicate uncertainty during volcanic crises. in *"Observing the Volcano World: Volcano Crisis Communication" Advances in Volcanology* (eds Fearnley, C. J. et al.) 571–583 (Springer, 2017).
59. Becerril, L. et al. Long-term volcanic hazard assessment on El Hierro (Canary Islands). *Nat. Hazards Earth Syst. Sci.* **14**, 1853–1870 (2014).
60. Ripepe, M. The onset of the 2007 Stromboli effusive eruption recorded by an integrated geophysical network. *J. Volcanol. Geotherm. Res.* **182**, 131–136 (2009).
61. De Gori, P., Chiarabba, C., Giampiccolo, E., Martinez–Arèvalo, C. & Patanè, D. Body wave attenuation heralds incoming eruptions at Mount Etna. *Geology* **39**, 503–506 (2011).
62. Del Negro, C. et al. Capturing the fingerprint of Etna volcano activity in gravity and satellite radar data. *Sci. Rep.* **3**, 3089 (2013).
63. Roult, G. et al. A new comprehensive classification of the Piton de la Fournaise activity spanning the 1985–2010 period. Search and analysis of short-term precursors from a broad-band seismological station. *J. Volcanol. Geotherm. Res.* **241–242**, 78–104 (2012).
64. Klein, F. W. Eruption forecasting at Kilauea Volcano, Hawaii. *J. Geophys. Res. Solid Earth* **89**, 3059–3073 (1984).
65. Patrick, M. R. et al. The cascading origin of the 2018 Kīlauea eruption and implications for future forecasting. *Nat. Commun.* **11**, 5646 (2020).
66. Gregg, P. M. et al. Forecasting mechanical failure and the 26 June 2018 eruption of Sierra Negra Volcano, Galápagos, Ecuador. *Sci. Adv*. **8** https://doi.org/10.1126/sciadv.abm4261 (2022).
67. Moreland, W. et al. Quasi-real-time hazard analysis of lava flows prior to the 2021 Fagradalsfjall eruption, Iceland. In *IVACEI 2023 Scientific Assembly* p. 745, Abstracts book, Rotorua, New Zealand. https://www.iavceivolcano.org/content/uploads/2021/03/iavcei-2023-book-of-abstracts.pdf (2023).
68. Yokoyama, I. Seismic energy releases from volcanoes. *Bull. Volcanol.* **50**, 1–13 (1988).
69. Telesca, L., Lovallo, M., López, C. & Martí, J. Multiparametric statistical investigation of seismicity occurred at El Hierro (Canary Islands) from 2011 to 2014. *Tectonophysics* **672-673**, 121–128 (2016).
70. Crosweller, H. S. et al. Global database on large magnitude explosive volcanic eruptions (LaMEVE). *J. Appl. Volcanol*. **1** https://doi.org/10.1186/2191-5040-1-4 (2012).
71. Ogburn, S. E., Loughlin, S. C. & Calder, E. S. *DomeHaz: Dome-forming Eruptions Database v2.4* https://vhub.org/resources/domedatabase (2012).
72. Geyer, A. & Martí, J. The new worldwide Collapse Caldera Database (CCDB): a tool for studying and understanding caldera processes. *J. Volcanol. Geotherm. Res.* **175**, 334–354 (2008).

Acknowledgements

I warmly thank Stefania Bartolini and Fidel Costa for their extensive reviews and contributions to a former version of this manuscript.

Author contributions

J.M. did all the work.

Competing interests

The author declares no competing interests.

Additional information

Correspondence and requests for materials should be addressed to J. Martí.

Reprints and permissions information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

© The Author(s) 2024