Deterministic Versus Probabilistic Volcano Monitoring: Not "or" But "and"

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Abstract

Volcanic eruption forecasting and hazard assessment are multi-disciplinary processes with scientific and social implications. Our limited knowledge and the randomness of the processes behind a volcanic eruption yield the need to quantify uncertainties on volcano dynamics. With deterministic and probabilistic methods for volcanic hazard assessment not always being in agreement, we propose a combined approach that bridges the two schools of thoughts in order to improve future volcano monitoring. Expert elicitation has proven to be an effective way to bind deterministic research within a probabilistic framework aiming to reduce the uncertainties related to any hazard forecast; yet, numerous exercises based on expert elicitation have revealed that the attempt to reduce uncertainties led to the creation of new ones, often unquantifiable, created by human nature and reasoning during stressful situations. Such reasoning ignores the complexity of volcanic processes and the fact that every scenario has a probability to occur. The recent probabilistic methods and tools marry probabilistic and deterministic approaches and lead to unprecedented models. Nevertheless, probabilistic hazard assessment is often misunderstood as not all of the researchers involved have backgrounds in such matters. A probabilistic method cannot stand-alone

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as it depends on data input obtained by deterministic approaches. We propose that, given the symbiotic relationship between the two methods, a probabilistic framework can play a role of moderator between various deterministic disciplines, thus creating a coherent environment for discussion and debate among seismologists, geodesists, geochemists. This can be achieved by training all scientists involved in hazard assessment, probability theory and data interpretation, while at least one group member objectively uses the information provided to produce the probabilities. Hence, numerical outcomes can be interpreted transparently as they represent the quantification of experts' knowledge and related uncertainties. A probabilistic method that incorporates the joint opinions of a group of multi-disciplinary researchers facilitates a more straightforward way of communicating scientific information to decision-makers.

Resumen extendid

La previsión de erupciones volcánicas y la evaluación del peligro son procesos multidisciplinarios, con implicaciones tanto científicas como sociales. Nuestro conocimiento limitado de los procesos detrás de una erupción volcánica y su aleatoriedad genera la necesidad de cuantificar las incertidumbres sobre las dinámicas del volcán y de mejorar la política de la toma de decisiones durante una crisis volcánica. Sabiendo que existe un desacuerdo sobre el uso de métodos determinísticos o probabilísticos durante la evaluación de la peligrosidad volcánica, revisamos ambos métodos y proponemos un enfoque que sirve como puente entre las dos escuelas de pensamiento y que pueda mejorar las capacidades de monitoreo volcánico en el futuro, hacia el reconocimiento en tiempo de manifestaciones volcánicas y amenazas relacionadas. La elicitación de expertos resulta ser una manera efectiva para relacionar la investigación determinística con el marco probabilístico para poder reducir la incertidumbre relacionada a cualquier intento de previsión de erupción; sin embargo, numerosos ejercicios basados en elicitaciones de expertos revelaron el hecho que este intento de reducir la incertidumbre creó nuevas incertidumbres, a menudo imposible de cuantificar, siendo generada por la naturaleza del pensamiento humano durante situaciones de estrés. El proceso general es sujeto a la personalidad de un/a investigador/a o un grupo de investigadores y sus ideas basadas en su experiencia. Esta manera de pensar interfiere con la complejidad intrínseca de los procesos volcánicos y con el hecho que cada escenario tiene una probabilidad de ocurrencia. Los métodos e instrumentos probabilísticos recientes juntaron los investigadores probabilísticos y determinísticos lo que resultó en modelos e interpretaciones de información sobre volcanes sin precedentes. Sin embargo, la novedad de la evaluación probabilística de peligrosidad es, a menudo, incomprendida debido al hecho que no todos los investigadores involucrados tienen una formación en estas materias teóricas. El método probabilístico no puede existir autónomamente ya que depende de datos de entrada obtenido a través de los estudios determinísticos. Proponemos que, dada la relación simbiótica entre ambos métodos, un marco probabilístico puede jugar el papel como moderador

entre las varias disciplinas deterministas, creando un ambiente coherente para discusiones y debates entre científicos (e.g., sismólogos, geodetas, geoquímicos). Este se puede obtener por medio de entrenamiento de todos los científicos involucrados en el monitoreo volcánico en la teoría probabilística y la interpretación de datos, mientras que al menos un miembro del grupo utiliza de manera objetiva la información disponible para producir las probabilidades numéricas. Así, los resultados numéricos pueden ser interpretados sin duda alguna, ya que representan la cuantificación del conocimiento de los expertos y las incertidumbres relacionadas. Un método probabilístico que incorpora las opiniones conjuntas de un grupo de investigadores multidisciplinarios facilitará una manera más transparente de comunicación de la información científica hacia las autoridades civiles, así mejorando (1) el proceso de toma de decisiones durante una crisis y la mitigación a largo plazo, y (2) el estado de medidas de preparación que incorpora los varios aspectos sociales. En el futuro, los reportes de previsiones emitidos por los científicos deberían incluir los resultados numéricos de los modelos probabilísticos; la arquitectura de monitoreo se debería expandir más allá del arreglo clásico "sismo-deformación-gas" hacia un arreglo "sismo-deformación-gas-probabilidad". Este capítulo de opinión pretende proponer una ideología posible, con el máximo respeto para el volcán, la sociedad, los científicos individuales o los grupos de científicos, y para las autoridades que toman las decisiones, con un objetivo común: mejorar la previsión de amenazas relacionadas a los volcanes para proteger la sociedad.

1 Introduction

Volcanoes are intrinsically complex and unpredictable systems manifesting non-linear behaviour in space and time, on the long- and short-term. Understanding how volcanoes evolve with time through the various stages of activity—from quiescence through unrest to eruption—is highly challenging. Awareness of these facts is a basic requisite when working with/on volcanoes. A major goal in volcanology is quantifying uncertainties on volcano dynamics, and learning how to translate these to decision makers and, occasionally, to the population. The combination of social implications and forecasting future behaviour of complex natural systems makes volcanology a rather unique but "tricky business". Besides the need to quantify uncertainties and better understand our limited knowledge on volcanoes it is necessary to legally protect volcanologists when exporting their knowledge outside their protected professional community (Bretton et al. 2015).

During the past 40–50 years, volcano monitoring and eruption forecasting during volcanic

crises has been largely dominated by the deterministic approach (Sparks 2003, i.e. most likely scenarios). Experts with different research backgrounds track changes in "their" parameters related to volcanic activity, afterwards discussed in "protected" round tables, generally behind locked doors, to eventually come up with a single voice. This single voice does not and should not reflect possible internal conflicts or disagreements behind the closed door. Such disagreement is an often-unstated expression of the uncertainty due to our lack of knowledge on volcanic processes, and the possible unavailability of data (i.e. epistemic uncertainty) and due to the intrinsic randomness of the volcanic process studied (i.e. aleatory uncertainty). The power of the single voice from the group of experts often misleads the receivers of the message (decision makers, authorities or lay public), believing the experts are "sure" on the evolution of volcanic activity. This is one of the reasons why volcanologists are often, correctly or incorrectly, highly trusted professionals by the public (Haynes et al. 2008; Donovan et al. 2011).

During the last decade, this "untouchable aura" around volcano monitoring based on deterministic research has vanished with the introduction of probabilistic hazard and eruption forecasting (e.g., Newhall and Hoblitt 2002; Sparks 2003; Marzocchi et al. 2004, 2008; Sparks and Aspinall 2004; Marzocchi and Bebbington 2012; Sobradelo et al. 2014; Sobradelo and Marti 2015). A recent chapter by Newhall and Pallister (2015) starts from the same false dichotomy, aiming to spouse the deterministic and probabilistic points of view in the highly applicable method of "Multiple Data Sets".

Marzocchi and Woo (2007) propose a rational on decision-making based on the hazard/risk separation principal, using a cost-benefit analyses as the guiding tool.

Among the methods for probabilistic hazard assessment and eruption forecasting, many are based on a Bayesian approach (e.g., Marzocchi et al. 2004, 2008; Sobradelo et al. 2014; Sobradelo and Marti 2015), that allows describing the probability of interest not as a single numerical value, but as a probability distribution. In this view, the probability of an eruption occurring, or of a given hazardous event hitting a target area, is described both by a best-evaluation value (for example the mean or the median of the probability distribution), and by a dispersion around such value (represented by standard deviations or by a confidence interval). These two quantities can be directly related to two different sources of uncertainty: the aleatory one and the epistemic one. In this way, Bayesian approaches allows quantifying also to what extent our probabilistic assessments are constrained by data and knowledge. In other words, now we know, as a group of volcano-experts, to which degree we can be wrong in our forecasts behind the closed doors. This black-on-white awareness brought to light by probability density functions has led to some key questions, from the in- and outside worlds: (1) are we, as volcano-experts, replaceable by a numerical approach?, and (2) we thought you, volcanologists, knew what was happening, but it seems you don't know.

This chapter critically reviews both "philosophies" of eruption forecasting and tracking of volcanic unrest and related hazards, in search of a combined approach that could become a guideline for future volcanic surveillance architectures. But we still need bridges between two schools (deterministic and probabilistic) apparently speaking a different language. Remember that both methodologies aim for the same goal: the timely recognition when volcanoes become hazardous in their various ways of expressions. This is our common professional and social responsibility as volcanologists.

2 Forecasts based on Deterministic Research

The goal of volcano monitoring based on deterministic research is to link temporal variations of physical-chemical parameters with variations in the state of unrest of the physical object volcano (i.e. unrest, magmatic unrest, non-magmatic unrest, eruption, hazard; Rouwet et al. 2014). Every volcanic eruption is intrinsically preceded by magma rise towards the surface. The major

aim in eruption forecasting is the quick recognition of such magma rise by changes in the physical parameters (deformation, seismicity) and chemical parameters. The most direct way to do so is to determine how, where, when and why the physical object "volcano" responds to magma rise.

Despite the straight-to-goal approach, large uncertainties exist: (1) a volcano remains a complex system (aleatory uncertainty), and (2) our knowledge on the volcano remains limited (epistemic uncertainty). How do we know if we have detected all the signals the volcano eventually releases? Which of these signals are we considering in our forecast framework, and why? Sometimes we may dismiss some signals as being not pertinent, or simply because we are unable to correlate them either with our 'understanding', or with the rest of the signals. Some 'signals' are considered as stand-alone, at the moment they occur, others are considered within a time evolution.

The quality of the forecast largely depends on the interpretation of the signals and the hypothesis/model of future activity developed as a result of this assumed scientific stringency. The latter is related to the experience and expertise of the deterministic researcher, or better, on how the experience and expertise is perceived by individual researchers or groups, decision makers and the researcher her/himself. It is known that the most informative and valid opinion may not always be that of the most respected or distinguished professional (Selva et al. 2012).

A big advantage in volcano monitoring based on deterministic research is the fact that, if independent monitoring approaches (e.g., geochemistry vs. geophysics) point toward a similar hypothesis on future hazard in time and space, the future scenario will become more likely. Finding a larger number of arguments in favour of certain scenarios is surely an efficient way to decipher volcanic unrest.

The timescale of the forecast is highly ambiguous and based on the limited knowledge on how the volcano (or analogue volcanoes) behaved in the past within the desired time-scale. Sometimes all the 'signals' converge towards an obvious conclusion, yet, there are numerous cases in which activity stopped or pulled back, sometimes for years before an actual eruption. So, the deterministic approach, which is based mostly on a recurrence interval and 'experience' of the volcanologist, is limited in providing a sound time scale for the evolution of the 'activity', and hence, for a forecast. In deterministic monitoring the "time" concept is not unambiguously defined, can be case dependent or even change within the evolution of an unrest phase. Fortunately, with converging signals through time, the monitoring time window often becomes narrower when building up towards increased unrest or eruption, although the exact time window cannot be rigorously chosen.

Besides the instrumental accuracies (detection limits, analytical errors, data quality), the uncertainty of the forecast cannot be quantified before an eruption. The only way to decrease this "unquantifiable" uncertainty is by increasing our knowledge on volcanoes, be it the specific volcano in unrest or any volcano that has shown similar behaviour in the past. The current development of methods to increase the quality (e.g., novel approaches, numerical modelling) and quantity of data (increase frequency, e.g., by remote sensing and real-time transmission) will undoubtedly help to achieve better insights into volcanic systems.

3 Probabilistic Forecasts

Probabilistic methods and tools for both short- and long-term time windows are more and more in the spotlight (Marzocchi et al. 2008; Sandri et al. 2009, 2012, 2014; Lindsay et al. 2010; Selva et al. 2010, 2011, 2012; Sobradelo et al. 2014; Sobradelo and Marti 2015; Bartolini et al. 2013; Becerril et al. 2014). A key review on probabilistic volcano monitoring can be found in Marzocchi and Bebbington (2012).

Within this opinion chapter, we highlight some critical aspects of the probabilistic forecasting method, without entering in the technical and operational details (see Tonini et al. 2016 and Sandri et al. 2017 for further reading).

A probabilistic forecast can provide a global but clear, numerical view of the opinion of, generally, a group of people, based on the volcanic history and knowledge of the volcano. Lately, probabilistic forecasts are more and more applied in real crisis situations. Thus far, the efficiency or accuracy have hardly been evaluated, probably due to the fact that only recently we are reaching statistically relevant numbers of cases to test this critical issue (Newhall and Pallister 2015). Once high numbers of applications are reached, the numerical outcomes of probabilistic methods can even be considered to support long-term hazard analyses, by becoming input information itself.

In practice, probabilistic hazard assessment and eruption forecasting frameworks constructed on the Event-Tree methodology (Newhall and Hoblitt 2002; Newhall and Pallister 2015) rely on a dataset of information about the past activity of a volcano (i.e. past data), theoretical/mathematical models (i.e. prior data) and a series of monitoring signals (i.e. parameters) that allow us to track the changes in the system with time (Marzocchi et al. 2008; Sobradelo et al. 2014). This information allows us to compute the probabilities of a specific hazardous outcome. As any such application reveals, the quality of the numerical output depends on the quality and quantity of the input. The risk exists that using a dataset for long-term probabilistic assessment will introduce an uncertainty, since the operators are often biased by the hypothesis or model coming forth of the dataset. Data should hence be considered "just" facts. In both deterministic and probabilistic hazard assessment, volcanologists rely on information about past eruptions: eruptive behaviour, eruption frequency, and eruption style. Such catalogues of information are inevitably incomplete. For instance, traces of smaller scale events could have been literally eroded away from the geological record, buried or masked by larger events and, hence, relics of precursory activity cannot be deduced. Consequently, one should limit the part of the catalogue used, for the period and specific kind of event you desire to forecast, for which it is reasonably complete. As such, the foundation of a probabilistic framework represents a source of

intrinsic uncertainty, that can somehow be overcome by quite robust methods for estimating completeness of sections of catalogues (Moran et al. 2011). The most intuitive solution, simply choosing a smaller dataset, usually representing the most recent years/centuries of a volcano's activity reduces this uncertainty. But this choice alone will be reflected in the quality of the probabilistic assessment. The unknowns of the data catalogue represent the uncertainty in a probabilistic framework, thus forcing volcanologists to 'select' how far to track back in time, and which information to use. In other words, we select e.g., only the last 300 years of activity of a volcano just simply because we believe to be more certain on what happened, instead of choosing the last 2000 years. What is the real scientific control of these choices? We cannot say with an acceptable certainty that a volcano will behave like it did in the last 300 or 2000 years. Indeed, with the recent probabilistic methods we are able to quantify the uncertainty of such choices but we are yet to find a sound scientific mechanism that allows us to make objective decisions regarding the data set. After all, the end goal of eruption forecasting is to give a prediction by analysing signals from an extremely complex system governed by a large degree of freedom.

Another aspect to tackle is the use of monitoring information, especially for short-term forecasts. Asking for numerical thresholds for monitoring parameters at the various nodes of event tree structures is intrinsically wrong, as a numerical threshold is an expression of certainty on something we cannot be certain about. For this, volcanologists use monitoring parameters in order to detect anomalies with respect to the volcano's background activity to be able to track their evolution with time. Moreover, from the beginning, we rely on a subjective choice when we define the unrest, unrest being commonly agreed upon as a state of elevated activity above background that causes concern (Phillipson et al. 2013). This cause of concern, expressed in numerical thresholds is a subjective choice: experts involved in volcano monitoring usually decide thresholds above/below which the

volcano is considered in unrest. But is a volcano really in unrest simply because we observe one day an anomaly in one of the parameters? And if so, how is the choice of a threshold scientifically sound, since most of the time it is based on the "expert's experience"? Of course, expert's experience should not be dismissed and never replaced by computer codes, but indeed, such a choice is associated with a large uncertainty that is extremely difficult to quantify. Even the act of reducing the uncertainty of such a choice relies on corroboration with information from other sources (e.g., analogue volcanoes) that is again subjective itself.

The "fuzzy-threshold approach" (upper and lower thresholds) somehow resolves this problem, as it tracks the degree of anomaly, emphasising from a state in which the volcano is 'not causing concern' to one 'causing a degree of concern'. Thresholds can be case-dependent and are therefore in most cases themselves biased. Especially in the case of poorly monitored volcanoes, or of volcanoes without a monitored stage of unrest (e.g., towards higher nodes in the event tree), Boolean (Y/N) parameters are highly preferable.

During an unrest crisis it might be tempting to adapt the numerical values of the thresholds, when e.g., the previous threshold is exceeded while the volcano does not "react on this parameter" as we thought it would have. Nevertheless, once thresholds for parameters are fixed, they should not be modified, in order to track the time evolution of probabilities (and related uncertainties).

4 Recommendations: Not "or" But "and"

4.1 Expert Elicitation: A Solution?

In general, any choice made by an expert panel regarding when a volcano enters a phase of unrest, what information is pertinent for hazard analyses and how to interpret the precursory signals is done by a discussion-based elicitation process. Each expert in a specific volcanological sub-domain will exercise their opinions, based on the experience they have, on every parameter within a monitoring setup, with the goal to reach consensus about the most likely scenario/threshold. All data and interpretations should be heard and evaluated. However, this process is still unduly influenced by the "stronger voice" of the group. We may be certain on something until someone else makes us doubt it. At the moment we start doubting our opinions we will be easily influenced by other, stronger opinions. On the other hand, volcanologists are often forced to make such decisions and be liable for their choices (in court of law, Bretton et al. 2015). The pressure of a volcanic 'crisis' and the feeling of liability increases scientists' reservations when faced with such choices.

A suggestion to improve the expert elicitation process is to introduce a person to act as a "Devil's advocate". This will mean that one of the experts is supposed to do exactly the opposite to the group's decision. If most of the experts agree on a scenario, it is the duty of the latter to completely disagree and evaluate the opposite scenario. This can be a good way to "account" for surprise scenarios. Other ways are to weight final results according to anonymous calibration tests (Cooke method; Cooke 1991; Aspinall et al. 2003; Aspinall 2006, 2010) and/or anonymous estimation of the most reliable members of the group, not necessarily the loudest.

The introduction of probabilistic hazard assessment methods in the multi-disciplinary volcanological community has first led to a discredit of the purely deterministic approach. After the usefulness of the probabilistic approach has been demonstrated, and confusion on the different philosophies has disappeared, or at least decreased, the awareness on framing the various "niche" research branches in a bigger picture resulted into constructive discussions among the various research groups and individuals involved. This results in coherent group thinking and a more collaborative atmosphere among volcanologists. Expert elicitation on its turn has obliged researchers with various backgrounds to absorb new data and ideas from one another. This is definitely a positive side-effect of the probabilistic approaches and expert elicitations.

4.2 How to Interpret Uncertainties?

Probabilistic volcanic hazard assessment and eruption forecasting is a relatively new concept in modern volcanology, and often reserved for those with a background in statistics. But, as reality showed (Constantinescu et al. 2016), most of the volcanologists are not fully aware of the probability theory and how its results should be interpreted. A panel of volcano experts usually comprises seismologists, geochemists, geodesists, geologists, petrologists, and not all of them necessarily have a background in probabilistic approaches, especially when such approach is based on the integration of opinions of all members of such a group. One idea to cope with this problem is to train the group members in how the probabilistic methodology works and how results should be interpreted, while another member of the group (the so-called "PROB-runner") objectively uses the information provided by the expert panel to produce the probabilistic forecast. In this way, the members of the group can interpret the numerical outcomes accounting for the associated uncertainty without questioning and second-guessing the output because they are already aware of the process (Newhall and Pallister 2015; Constantinescu et al. 2016).

The whole idea of the elicitation approach is to allow your mind to explore each possibility without influencing one of the possible outcomes just because one expert believes more in one outcome than the other. It is some sort of letting go. People don't like to admit they might be wrong, so the Event Tree and Cooke elicitation approaches allow them to anonymously change their views upon elicitation. If one is capable of admitting fallibility and look at the big picture with an open mind, allowing all possibilities to unfold, then full discussion can occur and resulting estimates of probabilities will eventually have lower uncertainties. In the end, the idea of probabilities is that all scenarios are possible to happen, some with a larger probability others with a lower one; all have probabilities (and related uncertainties) and nothing should be dismissed simply because 'I strongly believe it can't be, so I don't agree'.

4.3 Trust in Scientists?

Even the best scientists can make mistakes. If volcanic unrest or activity is badly forecasted, initial trust in scientists may dissolve in legal proceeding. Ideally, scientists who act to the best of their knowledge should be protected rather than being blamed if they make a bad forecast (Bretton et al. 2015). Trust in scientists depends on how these scientists are portrayed to society and actually how scientific aspects of volcanology are presented to the public. This should be a system with two-way feedback (Christie et al. 2015). Many countries lack volcano-education among communities, but people know that there are some scientists that 'know what they are doing'. People feel protected, but this is a false feeling of safety, propped up by ignorance of the real situation. When disaster strikes, scientists are often the first to blame. If the community will be involved fully in the mitigation and preparedness process (e.g., Gregg et al. 2004; Rouwet et al. 2013; Dohaney et al. 2015), they may be guided by 'compassion' and will understand that volcanologists cannot stop an eruption and protect people, and eventually the blame or trust too often falls on the elected authorities. Elected authorities should be the liaison between science and the general public. Trust is inherent when you are aware of the problem and the person dealing with it. Trust in scientists may grow because they successfully predict an eruption, but sustained growth in trust is due to multi-yearly exposure of the scientific staff to the public (Christie et al. 2015). This involves long years of planning, investing and engagement in educational campaigns. Trust is something that comes in time and involves a feedback loop between people and the scientists.

Within the current scope of this opinion chapter, the probabilistic method often seems to serve as a more transparent way of bridging between the scientists and the elected authorities (decision makers). First, the use of probabilities inherently implies some uncertainty, which in scientifically literate society is essential for public trust. Second, elicitation tools reflect a joint-opinion of a group of experts rather than of one. There is a need for

training and a full understanding of probabilistic results by the officials. The role of probabilistic tools should, in our opinion, not intervene in communication protocols with the lay public, but should be rather "restricted" to transmit information to decision-makers, representing part of the voice of the group of volcanologists. The efforts in communicating towards the lay public, in order to build "trust" amongst the population, should be decoupled from the background of the involved scientist (deterministic or probabilistic). Communication protocols are independent of the applied scientific method, and researchers should become more skilled to transmit their information openly towards the public, with the awareness of the uncertainty their information contains (Hicks and Few 2015).

4.4 Towards Collaborative Volcano Monitoring

A major accomplishment of the probabilistic method is to have increased harmony among the various deterministic research environments. This new dynamic favours the refining of previous conceptual models that originate from deterministic research, as the reference frame has become more complete.

Nevertheless, the probabilistic research approach is not yet fully accepted by the deterministic community due to criticism and anxiety to be "replaced" by the probabilistic method (VUELCO simulations Colima, Campi Flegrei, Cotopaxi and Dominica). This concern is unnecessary, since the first requisite for the probabilistic method to function is the availability of data, information, a priori believes and models, originating from deterministic research. More input information for the probabilistic method means significant decreases in the epistemic uncertainty of probabilistic outcomes.

Moreover, during volcanic crisis situations, deterministic researchers still stick to the "round table" approach and the lack of time inhibits to

efficiently interact with the researchers that run the probabilistic models (e.g., VUELCO simulation exercises). The latter need more detailed feedback and input information for single parameters at the various nodes of the event-tree. Despite refining the probabilistic model during pre-crisis by expert elicitations, in the heat of the moment of the crisis, a wrong interpretation of a numerical value provided by determinists will sometimes lead to disastrous numerical outcomes in the probabilistic models. The PROB-runner cannot be blamed for not being an expert in all fields in volcanology, incorporated through parameters in e.g., BET or HASSET.

Three solutions to this crucial issue are proposed: (1) probabilistic model runners should actively take part in the "closed-door" discussions by the experts from the various fields, before incorporating numerical values in probabilistic models, (2) a separate team of experts that profoundly know the needs and functioning of probabilistic models should flank the PROB-runners during crisis. Both realities are not yet accomplished, and/or (3) an event tree structure, put forward by a facilitator between the deterministic and probabilistic research teams should serve as the base to guide scientific discussion and get fast to the nucleus of the crisis (Newhall and Pallister 2015). Future simulation exercises on volcanic crisis situations should focus on this training approach, in order to be prepared when real the crisis strikes.

Moreover, the outcomes of probabilistic models have to be included in the final reports transmitted to authorities, and be respected as one of the many monitoring tools, without decreasing or increasing their weight and value within the still deterministic-dominated general opinion. Since a probabilistic framework offers a measure of the uncertainty, any interpretation should not be taken for granted, neither decision makers should make decisions based solely on a probability. Probabilities should be considered as an addition to the information upon which decisions are made, and not as a decisive factor.

5   Take Home Ideas

Probabilistic forecasting has become an inherent part within a multi-facet view of research and volcano monitoring; neither deterministic, nor probabilistic methods, can or should stand alone. More than being a means to transmit information between volcanologists and decision making authorities, probabilistic models should also be based on, and promote, deterministic research that can be written up after "round table" discussions (Fig. 1).

Incorporation of probabilistic models in volcano monitoring has many advantages: (1) protecting against oversimplified, over-confident forecasts. Even though decision makers may initially have difficulties to understand uncertainties and prefer black-on-white numbers, Y/N forecasts, they will soon come to appreciate probabilities if they are represented in an understandable way; (2) creating harmony amongst the volcanological community because probabilities will reflect the general view of the monitoring team, and (3) legally protecting the entire monitoring team by probabilities and their uncertainties as forecasts are perfectly traceable and reproducible, if disaster strikes after "erroneous forecasts". However, to date, probabilistic forecasts have not been rigorously evaluated to know whether they are an improvement over traditional, non-probabilistic forecast methods. For sure, they do better than traditional methods at estimating uncertainty. We still need tests on whether they are more accurate, and more useful for decision makers than older methods (Newhall and Pallister 2015).

In the future, reports should include the forecast of probabilistic models; a monitoring architecture should expand beyond the classical "seismo-deformation-gas" setup and become "seismo-deformation-gas-probability" setup (in random order of importance) (Fig. 1). Probabilistic models cannot stand alone, as they need the input and feedback from deterministic research. "Probabilists" should not communicate their numerical outcomes directly to the decision-making authorities: it is better to convey the opinion of an entire group. Probabilistic methods can serve as "moderator" among the various disciplines, while expert elicitations are the "glue" between the deterministic and probabilistic approaches (Fig. 1). Probabilistic methods should knock down walls and stimulate discussion and coherence amongst the various research branches (seismologists, geodesists,
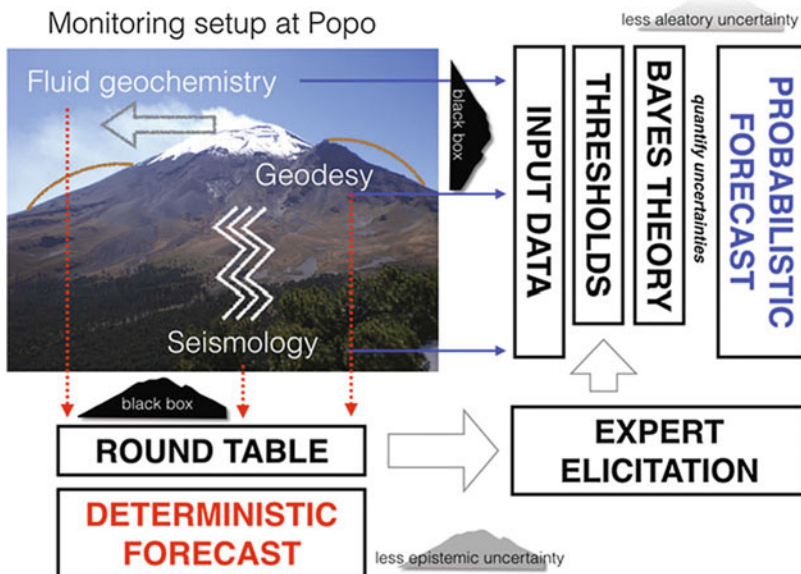

Fig. 1 From dichotomic monitoring setups (deterministic vs. probabilistic forecast, "or" setups) to an "and" strategy. The picture shows VUELCO target volcano Popocatépetl, Mexico (November 2011, D.R.). Before interpretation of the data (monitoring data, eruptive history or any a priori model) the volcano is considered a "*black box*"

geochemists, petrologists, geologists). This requires time, effort and an open-mind by all involved parties/volcanologists in volcano monitoring.

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