State of volcanic eruption forecasting: needs, challenges and opportunities

Warner MARZOCCHI[1], Graham LEONARD[2], Kyle ANDERSON[3]

1. University of Naples, Federico II
2. Earth Sciences New Zealand
3. U.S. Geological Survey

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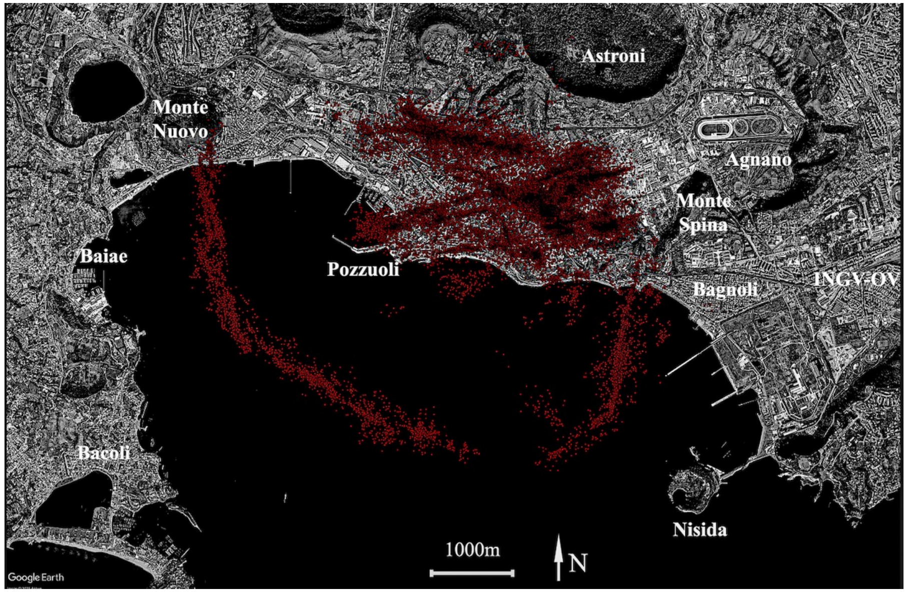
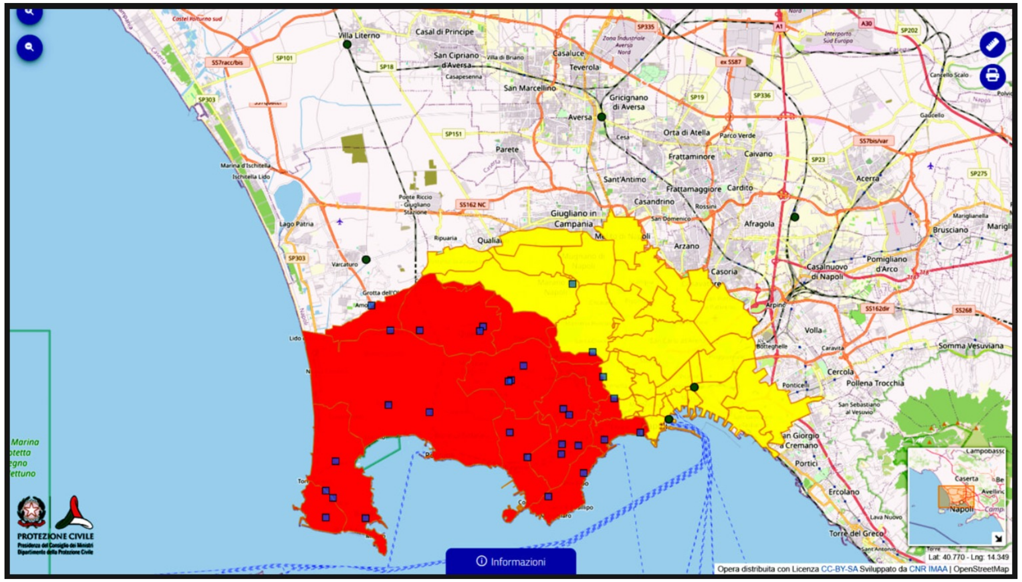
How does eruption forecasting enable action to reduce risk? (1)

During **unrest**, **volcanic risk** is usually decreased by **reducing the exposure** (e.g., evacuating people, or diverting flights)



Current seismicity at Campi Flegrei (Xing et al., 2025) showing the areas more affected by superficial earthquakes



Campi Flegrei evacuation zone in case of expected eruption

How does eruption forecasting enable action to reduce risk? (2)

- **The call for an evacuation** is often based on substantial scientific **uncertainty,** in particular if we want to **have enough time** for an orderly evacuation.
- **Decision-making under uncertainty** implies that we cannot evaluate the **rightness** of a decision *a posteriori*, but the **decision-making ought to be defensible.**
- This is **particularly important** for **high-risk volcanoes** where the mitigation actions can be costly and challenging
- Often the **Volcanic Alert Level (VAL)** scheme is used, but it is **not always clear** when to move from one level to another one.

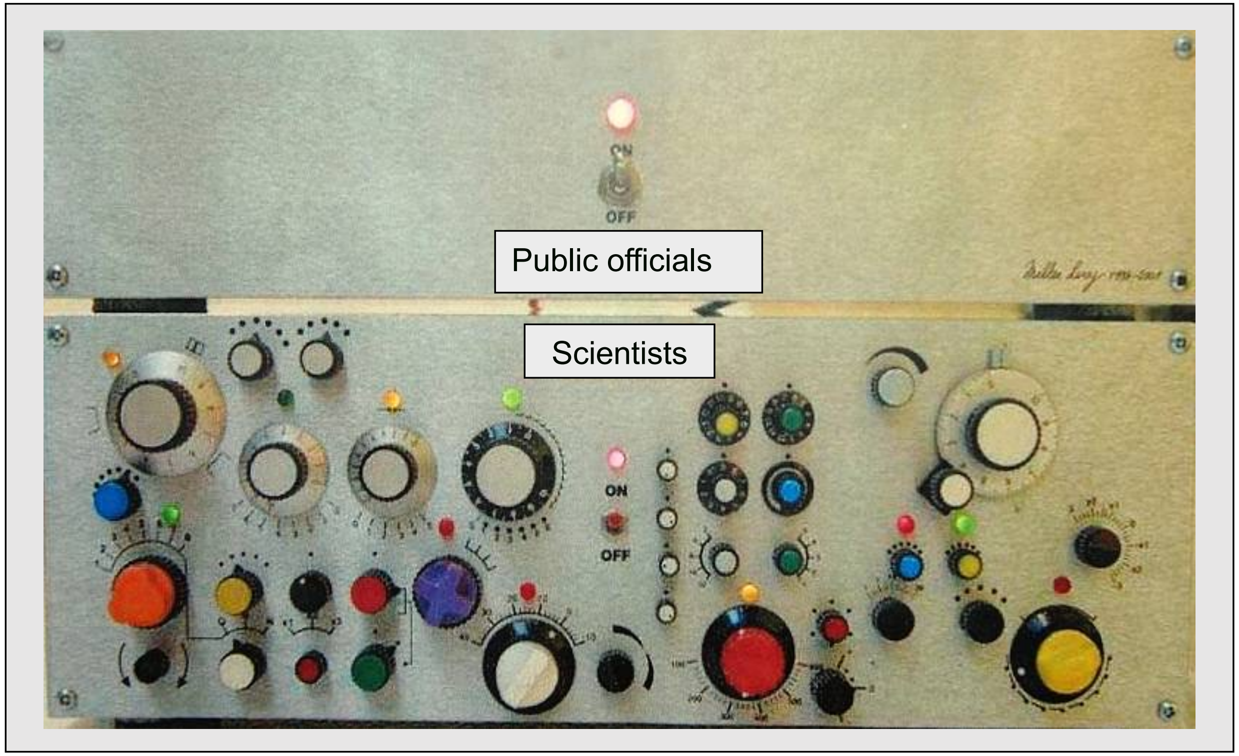
«Don’t judge human actions by what happens»

(J. Bernoulli, more than three centuries ago)

How does eruption forecasting enable action to reduce risk? (3)

Some conceptual issues behind decision-making under uncertainty

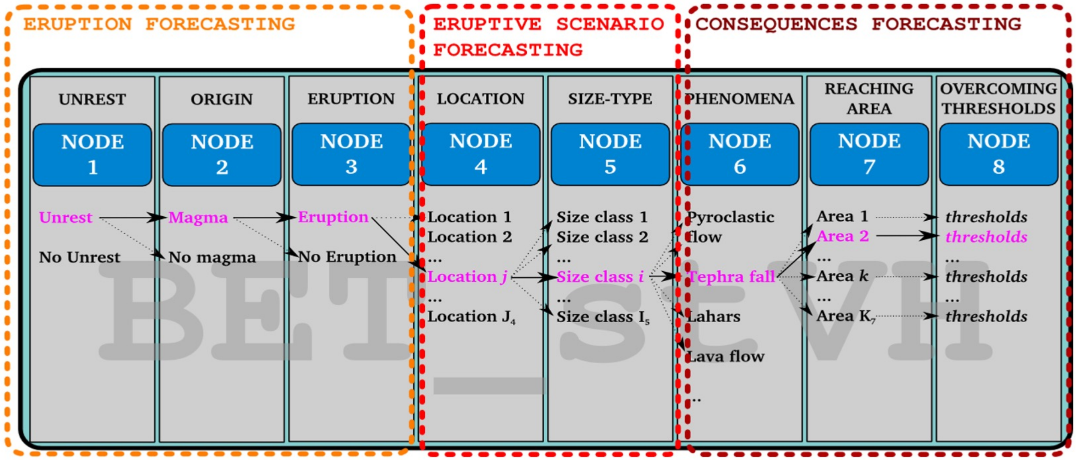
- The link between **science** and **decision making** requires to map a continuous number (the **probability**) into a Boolean logic (**go – not go**) of the decision makers
- This can be made defining **thresholds in probability**. These thresholds do not have any scientific value, but they must account for **many factors that go well beyond volcanology.**



State-of-the-art: probability

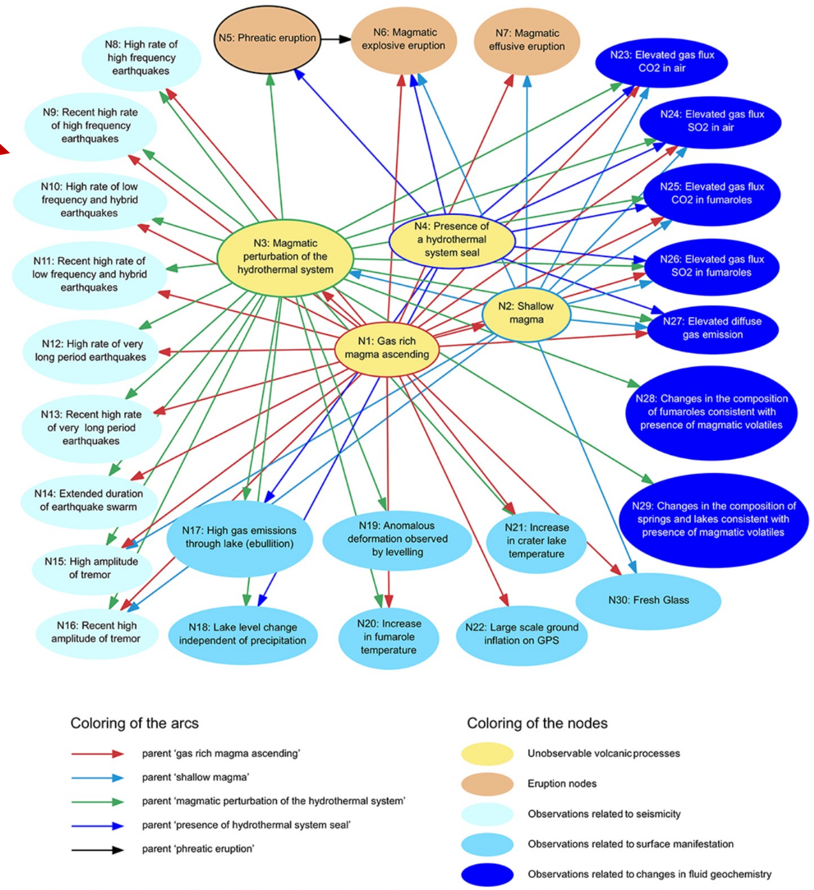
The most common way to handle quantitatively all kinds of pervasive and unavoidable uncertainty is through **probability**.

(Bayesian) Event Tree and **Bayesian Belief Network**



Marzocchi et al., 2008

Christophersen et al., 2018



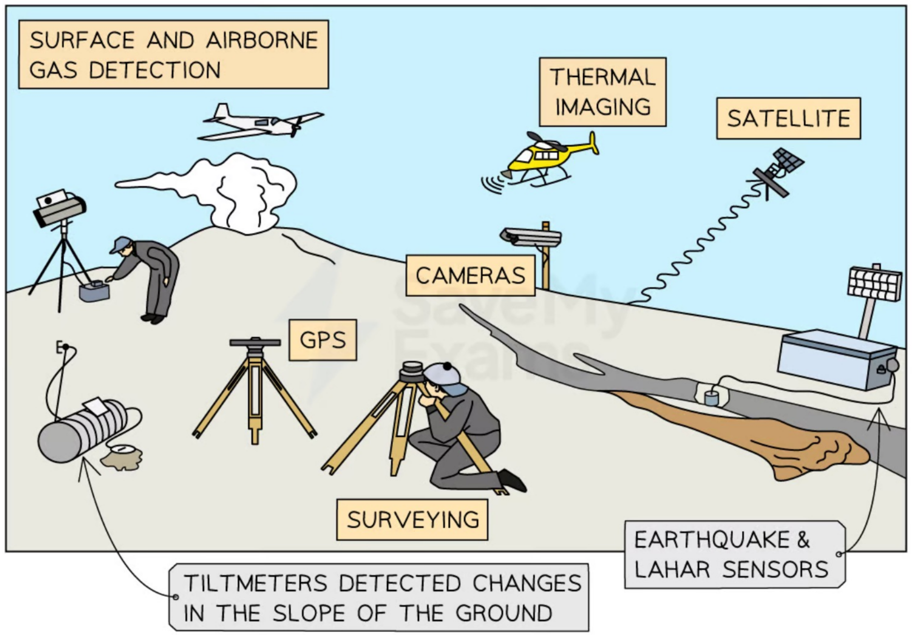
Basically, all these methods translate **volcanological information and experts' judgment into probabilities**

State-of-the-art: diagnostic monitoring signals

Predictions (Deterministic statement YES-NO) are based on the search for **diagnostic precursory monitoring signals** that anticipate an eruption.

Their existence in a time frame usable for risk reduction actions would **greatly simplify the decision-making process** (no need to establish **thresholds** and no **responsibilities**!).

Grasso & Zaliapin, 2004)



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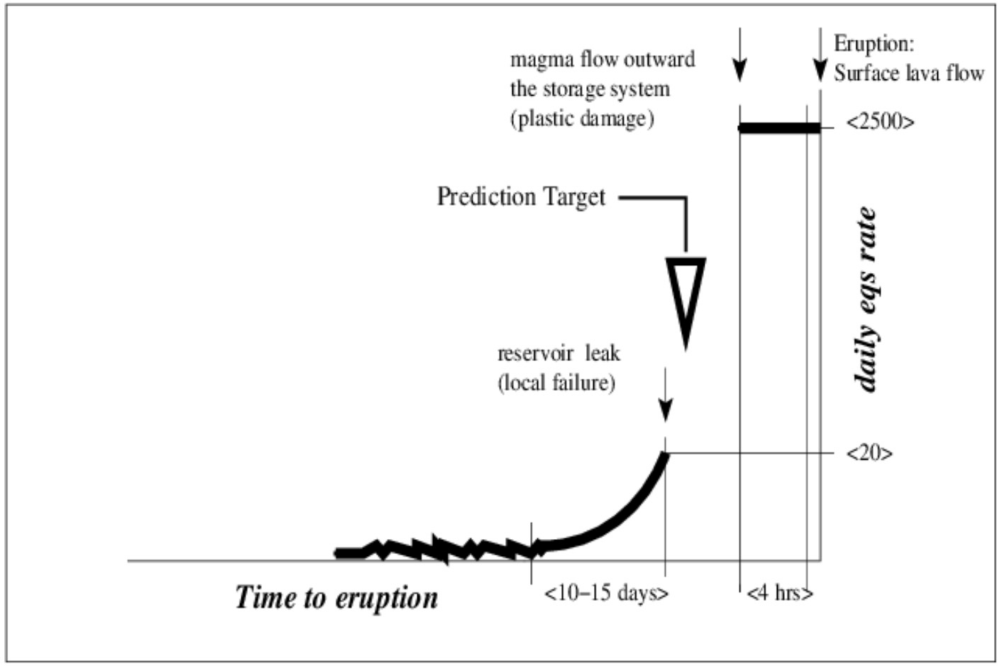
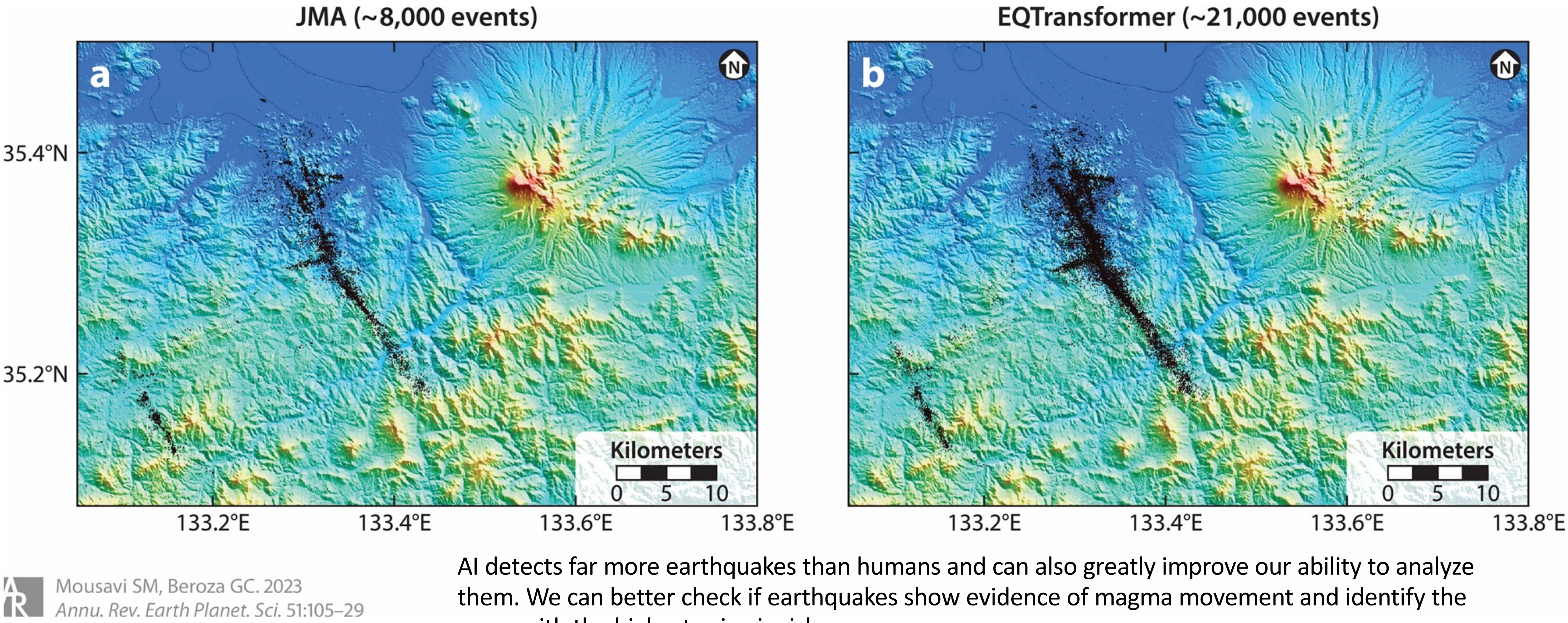


Average pre-eruptive pattern before a PdIF eruption. This behavior is obtained by averaging the seismicity rate over the 15 eruptions during 1988-2001.

State-of-the-art: machine learning and artificial intelligence

Improved **detection** and **analysis** of patterns, particularly for large-volume data sets

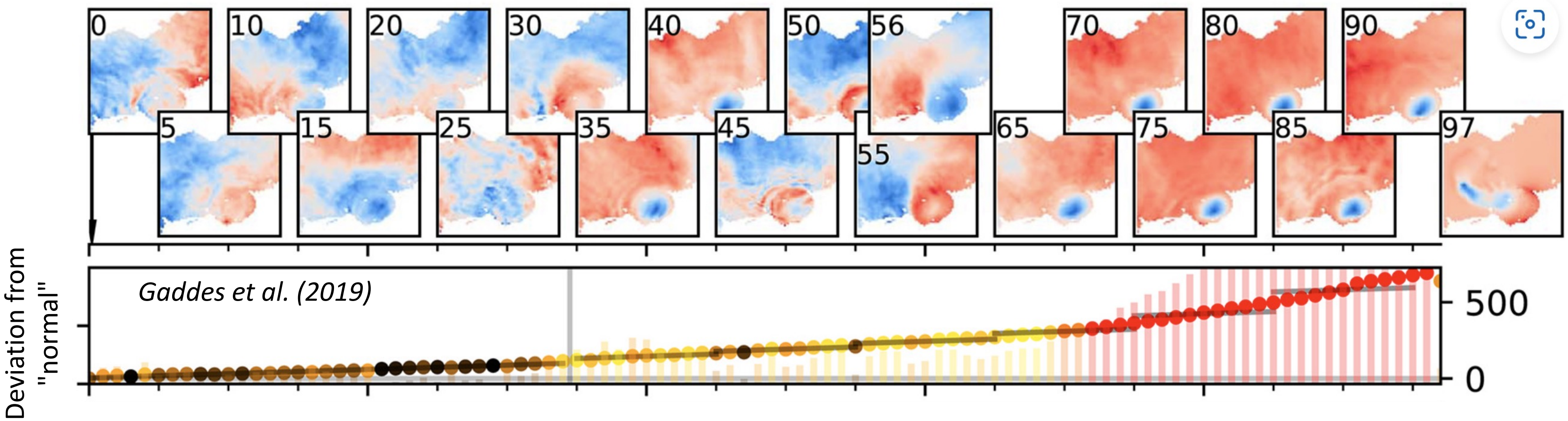
Earthquake detection



AI detects far more earthquakes than humans and can also greatly improve our ability to analyze them. We can better check if earthquakes show evidence of magma movement and identify the areas with the highest seismic risk.

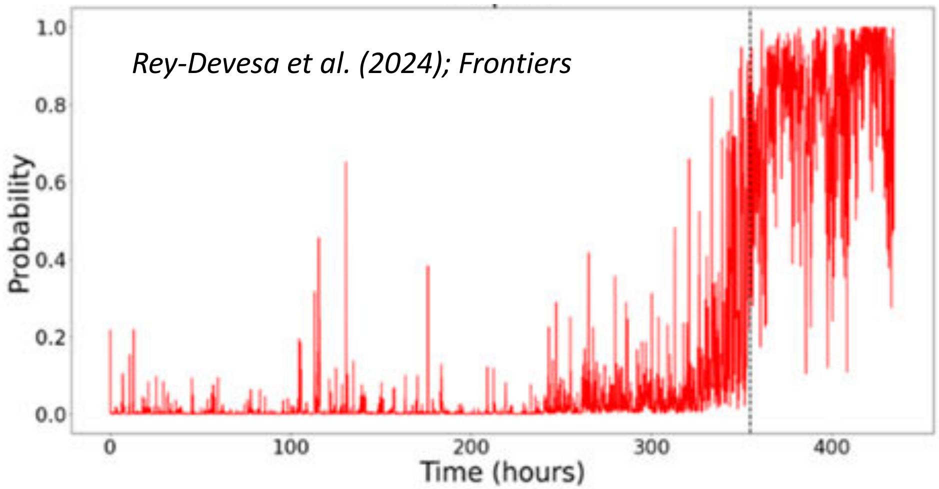
State-of-the-art: machine learning and artificial intelligence

Pattern detection can give us change detection and quantitative early warning



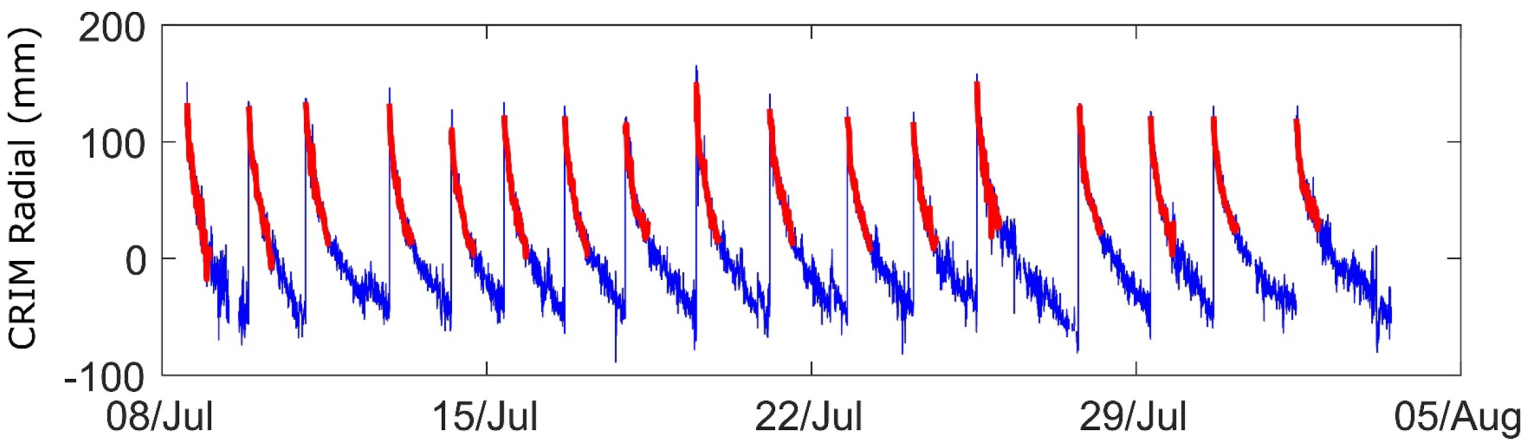
Remote sensing (InSAR) data for anomaly detection & early warning at Sierra Negra

Seismic data for early warning at Colima



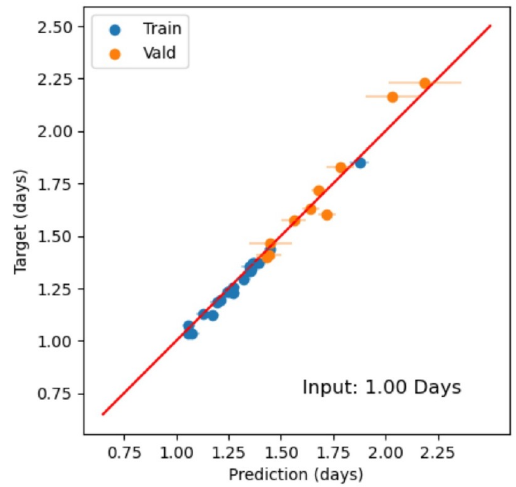
State-of-the-art: machine learning and artificial intelligence

Extrapolating patterns can give us forecasts



McBearty & Segall (2024); JGR

Forecasting **caldera collapse cycles** at Kilauea volcano using a graph neural net (GNN)

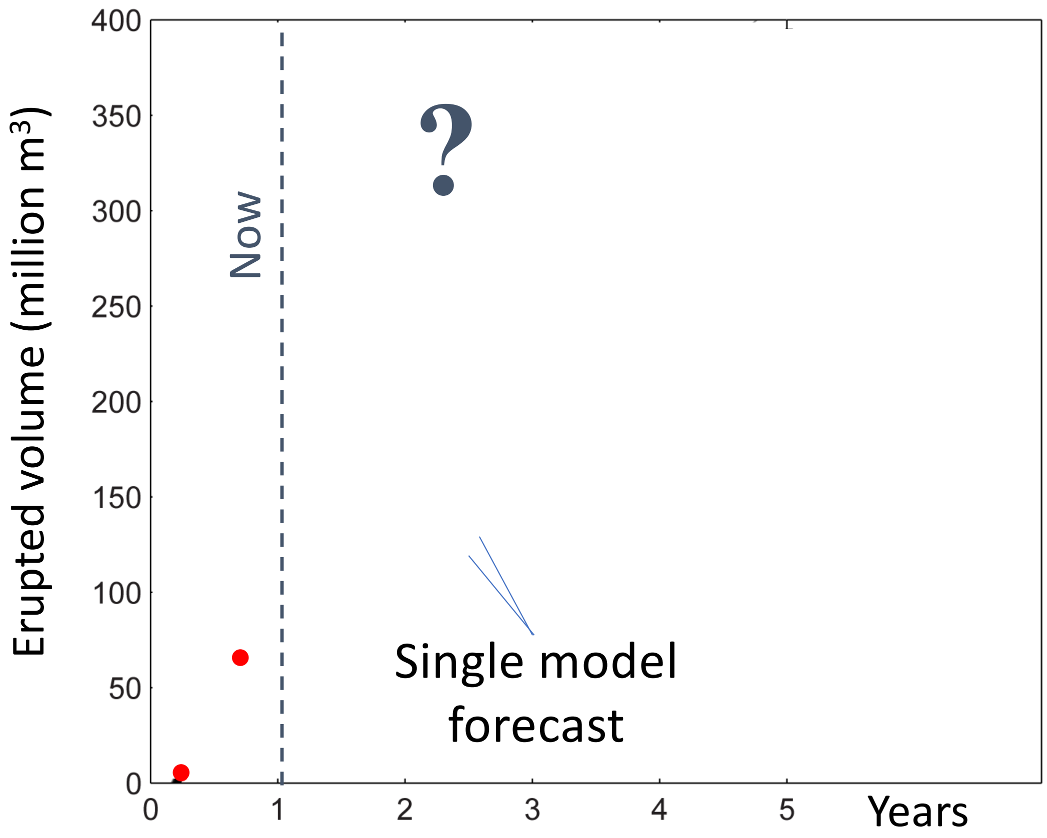


McBearty & Segall (2024); JGR

Challenges:

- "Black boxes" (difficult to justify or explain outcomes)
- Limited training data for many datasets and volcanoes – but some learning can be transferred (e.g., *Ardid et al. 2025; Nat. Comm.*)

State-of-the-art: volcano physics (+ probability)



Probabilistic forecasts are conditioned on uncertainties in the state of the system (magma pressure, rock properties, etc.) and the data

Physics-based forecasts are increasingly common for hazards (tephra, lava flows) but still rare for deeper processes (although see examples at St. Helens and La Palma; Mastin et al. 2009, Charco et al. 2024; Esse et al. 2025).

Why? Challenges include:

- Highly nonlinear physical processes that cannot be observed directly and are constrained by relatively little data
- Volcanoes can be "snowflakes" (need to develop a new model during a crisis?)

This is a difficult challenge; physics-based forecasts must be used as part of a holistic probability framework to mitigate their limitations.

Needs, challenges, gaps, uncertainties and opportunities (1)

SCIENTIFIC NEEDS and GAPS:

- Presently, many volcanoes are not monitored. We need more & better data, in open databases to establish 'base rates', build & test models

- We need to better utilize the data we already have (detection, analysis, warning, extrapolation)

- Better models to connect monitoring signals to eruption probability (real-time, interdisciplinary)

- Approaches to probabilistic long-term forecasts to support land use planning, adaptation, built recovery that can truly reduce risk

Needs, challenges, gaps, uncertainties and opportunities (2)

DECISION-MAKER NEEDS:

- We need protocols (like doctors) to justify all contributions and responsibilities in the decision-making process at any stage. So far, no protocols are in place.

- Agreed guidance, standards, training, evaluation to support the connection of science to decisions - similar to WMO global activities for weather.

- Approach to explicitly handling and communicating uncertainty in the science to decision interface.

- Warnings of impact, not just the process at a volcano

Needs, challenges, gaps, uncertainties and opportunities (3)

Challenges:

- **Estimating and communicating probability of eruption**, including epistemic uncertainty, in a crisis, preserving credibility (*communicating uncertainties has never been a popular undertaking*)
- Perception of protection from monitoring and forecasts by public and decision-makers - can **perversely increase risk** as a cop-out to decide not to reduce risk but instead rely on warnings.
- We still **lack reliable precursors** about the size of the impending eruption, and precursors are often absent for the smaller eruptions.
- Gas driven eruptions onset (including phreatic) is **fast and often not anticipated by precursors**. This is a problem in many situations, e.g., for tourists that often go very close to the volcano.
- **Most forecasts are based on empirical evidence**. This is a challenge for poorly monitored volcanoes or those that are reawakening. We need to learn better how to transfer knowledge between volcanoes, accounting for huge differences between volcanic systems (search for analogs!)

Needs, challenges, gaps, uncertainties and opportunities (4)

- Globally trained history-monitoring-forecast models
- Learning from the parallel to weather incl. landslide, tsunami, wildfire
- Harnessing rapidly evolving tools from the AI community
- Support of managing the demand for earthquake early warning and short-term forecasts alongside these.
- Multi-hazard consistent impact-based forecasts, connected to risk calculation for impact.
- Integration with human behaviour and communications (warnings that trigger the right protective action, in time, with people aware of the risks they are taking and the reality of protection (or not) from the forecast opportunity)
- Multi-hazard risk reduction in the face of climate change is becoming higher demand, more visible, and more necessary (to reduce cost, maintain insurance) - so the uptake of long-term forecasts of large eruptions alongside weather and other risk maps should be growing.

What is the minimum capability for volcanic eruption forecasting?

Volcanoes are monitored and studied in a very inhomogeneous way.

Conceptually, a minimum requirement for forecasting is to have:

- A **rationale and coherent summary of the scientific knowledge on the volcano**. E.g., which kind of monitoring anomalies are relevant, or not, for that volcano; which kind of eruptions happened in the past; etc. This is crucial to establish a **skillful experts' judgment information.**
- Monitoring data that can be **accessed and interpreted in (quasi) real-time**. Earthquakes, and deformation data are likely the easiest parameters to be interpreted (not necessarily the most important ones) for **skillful forecasting**.
- Strong understanding of **strengths and limitations of forecasts** between scientists, decision-makers and public, so that expectations are calibrated, and hopes of risk reduction are realistic.
- **Forecast integration with communication, warning, evaluation** so that the system is as effective as possible and tested and understood by all in terms of the real effectiveness (or not).

What next?

Quantitative volcanology is still pretty young! Hence, we should improve significantly in many fields.
Here just a few general thoughts.
(But please keep in mind that predicting the evolution of Science is likely more difficult than predicting eruptions!)

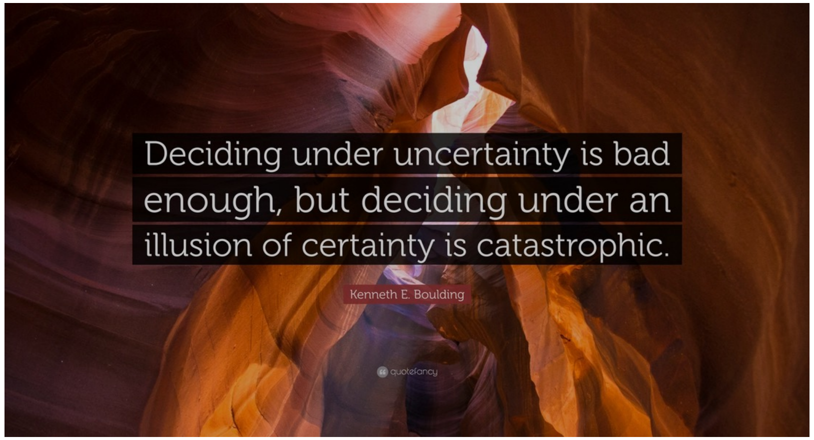
- Improve **monitoring systems** and **data sharing** among volcanoes, in a way that any researcher can learn also from "analogs" volcanoes (e.g., WOVOdat initiative).
- Improve **forecasting models**, based on **different perspectives** (physics-based, empirical, Artificial Intelligence).
- Explore and establish methods to **test the forecasting models**. A model can be used for societal purposes only if it is reliable and/or widely accepted by a large community.
- Work more closely to decision-makers to establish protocols that describe the whole decision-making process, and the **role and responsibilities of all actors involved.**
- **Multi-hazard (with weather etc.) impact-based (ie. with risk calculation) forecasts are the future.**
  - **Timescales** – ideally long-term (for reduction/adaptation/built-recovery/insurance), short-term (like weather), now-casting (what's happening now), and recent-hindcasting (with impact data, for response) are on a common or at least compatible basis.

Role of collaboration in addressing volcanic eruption forecasting

- Experts from different fields (seismology, ground deformation, geochemistry, etc) and competences (volcanology, physics, mathematics, statistics, social science etc) are to work together with the same goal of **improving eruption forecasting**, which is a markedly **multidisciplinary field**. This require a substantial effort to create a **common language** and **terminology** and to understand how any **single field can contribute** to the final goal.

- Decision-makers are to work with scientists to understand the scientific input and the associated uncertainties. Rational decision-making requires information and competences that are **well beyond volcanology. Collaboration across multi-hazards for all is also key.**

- The collaboration between scientists and decision-makers on how to describe and handle uncertainties must be described in **protocols**. Protocols are to be **available before crises** in a way that anybody can scrutinize and evaluate them, before things happen. These protocols may be also a very **powerful communication tool** and are of tremendous importance for high-risk volcanoes where risk mitigation actions can be very costly. Arrangements need testing, in exercises, for improvement.

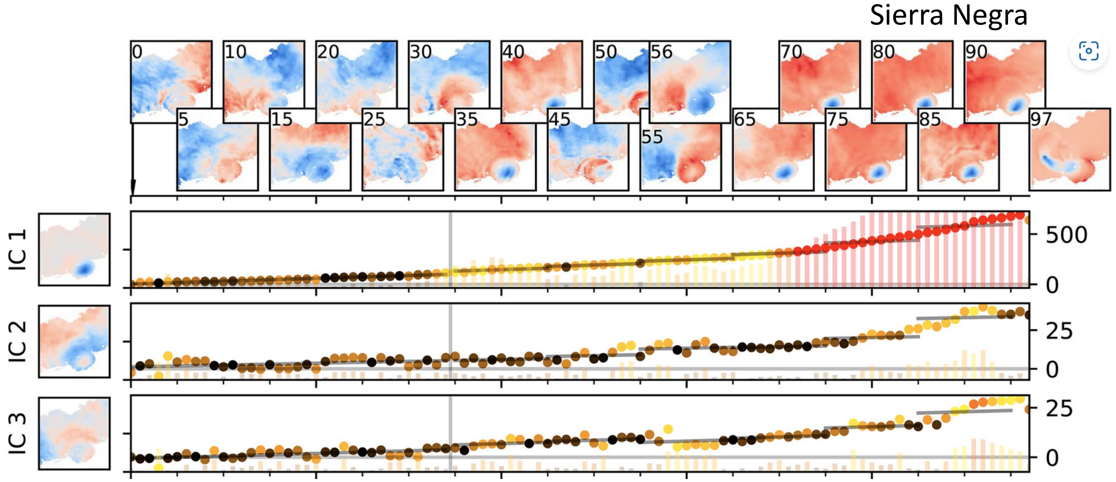



Warning!
Irresponsible
people working

State-of-the-art: machine learning and artificial intelligence

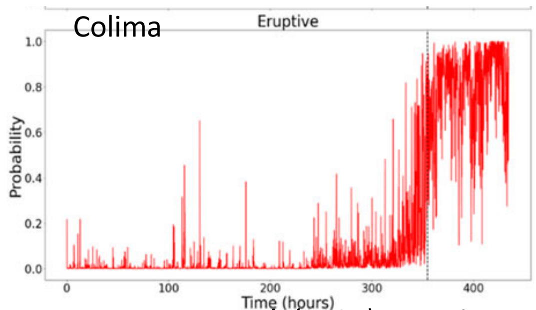
Improved **detection** and **analysis** of patterns = early warning

Ground deformation detection & warning



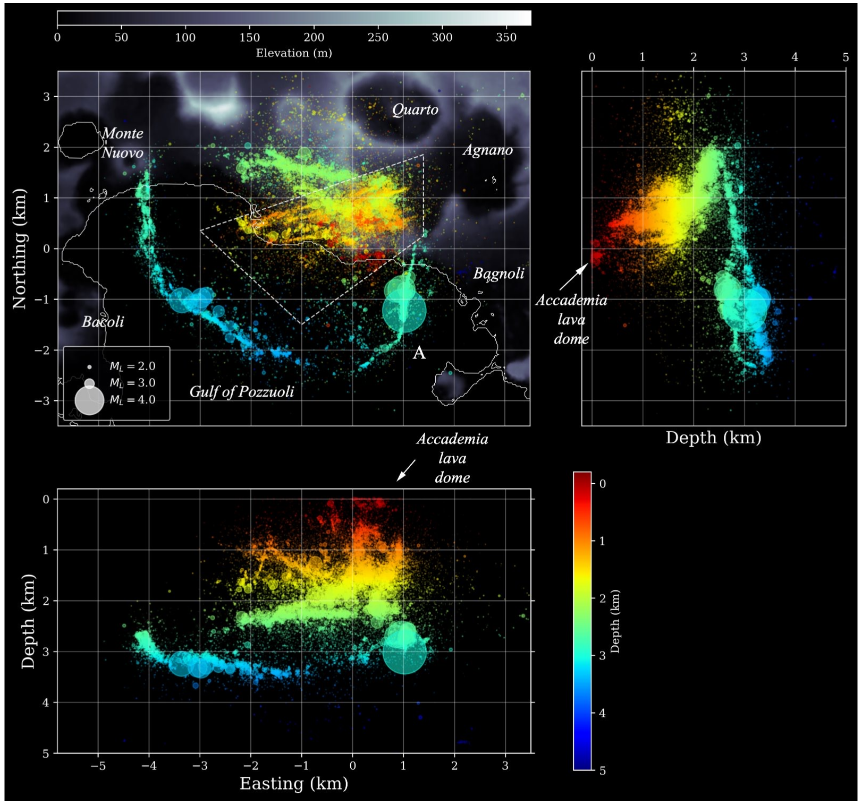
Gaddes et al. (2019)

Seismicity detection & warning



Rey-Devesa et al. (2024); Frontiers

Earthquake detection

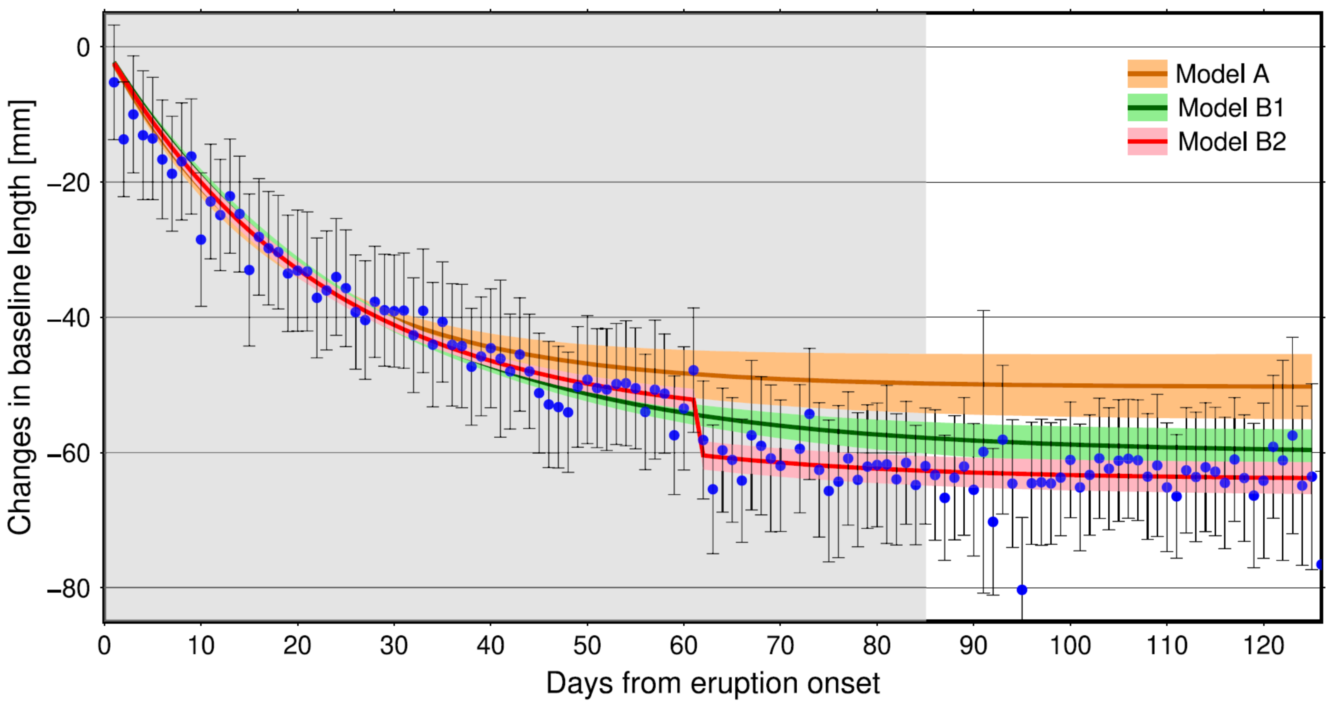


High-resolution earthquake catalog of the current unrest at Campi Flegrei. We can check if earthquakes show evidence of movements of magma and identify the areas with the highest seismic risk.

State-of-the-art: volcano physics (+ probability)

Physical models of volcanic processes can be used to forecast future activity

- Models may range from extremely simple to extremely complex
- The use of an(multi-)ensemble strategy includes all models in a proper way (weighting them)



Esse et al. (2025)

Can we forecast eruptions the way we forecast the weather?

- Based on physics
- Conditioned on data
- Fully probabilistic