EARTH AND ITS RESOURCES
Published: 28 March 2022
doi: 10.3389/frym.2022.813910

HOW SCIENTISTS FORECAST VOLCANIC ERUPTIONS

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AGES: 8–9

Volcanic eruptions are impressive demonstrations of the activity of our planet. While some eruptions may be safely observed from distance, many eruptions, especially if explosive, may be hazardous to the populations and the environment around the volcano, including the animals, plants, and manmade structures. To reduce harm caused by eruptions, scientists called volcanologists attempt to forecast eruptions. Although volcanoes commonly provide several kinds of warnings before erupting, there is no single warning signal that allows volcanologists to accurately predict every eruption. Instead, data from various types of monitoring instruments are combined to help scientists forecast eruptions at least a few days in advance. In the next decades, as volcanologists improve monitoring systems and better understand the processes happening inside volcanoes, more precise eruption forecasts will be possible.

VOLCANOES: A NATURAL HAZARD

Our planet experiences several types of natural hazards, including earthquakes, volcanic eruptions, landslides, tsunamis, hurricanes,

Figure 1

(A) The Mount St. Helens volcano (USA) before (left) and after (right) the 1980 eruption (Image credit: USGS). The explosive eruption destroyed the top and a side of the volcano; it also destroyed the surrounding forest, including the trees in the foreground, leaving a blanket of ash formed by the exploded magma[1]. **(B)** The eruption of the Usu volcano (Japan) in 2000 changed the ground below the house, covered the roof with volcanic ash, and pierced the roof with falling bombs of magma.

[1] Visit https://pubs.usgs.gov/gip/msh/catastrophic.html to see what happened between the two images shown here.

and tornadoes. Volcanic eruptions can vary in size, with the largest being the most devastating of natural hazards, capable of impacting the entire planet (Figure 1). Luckily, these destructive events are rare—usually occurring approximately once every 100,000 years—whereas the most frequent eruptions, occurring approximately every week, are mild and impact only small areas.

There are ∼600 active volcanoes on Earth, mainly along the boundaries of the mobile tectonic plates that make up the outer shell of our planet. It is estimated that about 800 million people—one-tenth of the world's population—live near active volcanoes. Volcanic activity has claimed the lives of nearly 300,000 victims in the last four centuries [1]. The last major destructive event was the Nevado del Ruiz eruption in Colombia, in 1985. This eruption was only of moderate size, but it caused more than 23,000 casualties in a matter of minutes. Even if they do not cause human deaths, eruptions can impact the environment, including animals, plants, and man-made structures like buildings, roads, railways, airports, factories, and power plants. During the Eyjafjallajokull eruption in Iceland in 2010, for example, the ash cloud from the eruption spread through the atmosphere and halted the air traffic over Europe for several days, stranding 10 million passengers and resulting in the loss of $5 billion (US).

To reduce the impact of volcanic eruptions on humans and the environment, scientists called volcanologists must be able to forecast when and where volcanoes are going to erupt. Forecasting volcanic eruptions allows people to be alerted so they can evacuate, reducing the negative impact of eruptions on human populations.

HOW VOLCANOES WORK

To forecast eruptions, volcanologists must first understand how volcanoes work.

Volcanoes are usually in a silent, "resting" state, when the magma below them does not move or accumulate. Sometimes the magma rises toward the surface and, when it stops rising, it accumulates within the rock that makes up the Earth's crust. This accumulation of magma eventually forms a magma chamber. The magma chamber can change the shape of the surrounding rock and create fractures in the Earth's crust that can cause earthquakes. Earthquake activity is called **seismicity**. The fractures also serve as pathways that allow gases to escape from the magma into the air. This is called **degassing**. The accumulating magma slowly enlarges the volcano through **deformation**.

SEISMICITY

Occurrence of earthquakes in an area.

DEGASSING

Release of gases, usually related to the magma below, from the crater or other portions of a volcano.

DEFORMATION

Change of shape; the part of the volcano above the Earth's surface or the rocks below it may deform.

UNREST

State of a volcano with seismicity, degassing and deformation that can precede eruption.

When the volcano passes from a silent phase to an "excited" phase when seismicity, degassing and deformation occur, this is called **unrest**. The unrest phase can last from days to months, and it is considered a warning from the volcano it is unstable and that there may be an eruption. Most eruptions are preceded by unrest, but not every unrest episode ends in an eruption—sometimes after unrest a volcano may become silent again. So, although unrest does not always precede eruptions, its appearance is the main clue for volcanologists to forecast eruptions.

To make a reliable eruption forecast, volcanologists must understand what exactly happens during unrest, by analyzing the signals sent out by the volcano. Unrest is usually detected and studied using a precise monitoring system, consisting of a group of sensitive instruments that record the real-time activity inside a volcano, particularly the movement of magma. Therefore, monitoring the seismicity, degassing, and deformation produced by the moving magma allows volcanologists to understand what is happening in a volcano during unrest (Figure 2). Mathematical models use this monitoring information to define the size, shape, and location of magma producing the unrest [1].

While many volcanoes are monitored, several volcanoes, especially in remote areas, are monitored poorly or not at all. Forecasting eruptions obviously depends on the availability of a monitoring system that can detect unrest.

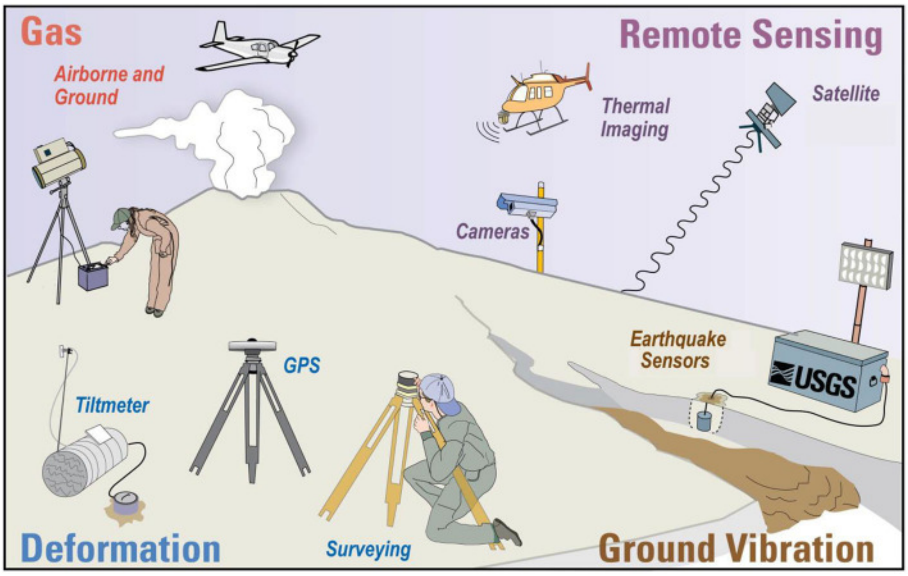

Figure 2

Figure 2

Frequently used volcano monitoring techniques include GPS, InSAR, and tiltmeter, which are techniques to measure deformation; surveying, in which volcanologists directly examine the volcano; thermal imaging, which detects temperature variations on the volcano (Image credit: US Geological Survey, USGS; https://volcanoes.usgs.gov/vhp/monitoring.html).

CURRENT FORECASTING APPROACHES

Volcanologists have used two kinds of approaches to forecast eruptions. First, they have tried to predict *for sure* (yes or no) whether an eruption is coming. This is called a **deterministic** approach. More recently, they have been trying to forecast whether an eruption is *likely* or not, using a percentage of likelihood. This is called a **probabilistic** approach.

DETERMINISTIC

Exact prediction (yes or no) of whether an event (like an eruption) will occur.

PROBABILISTIC

An uncertain forecast, defined as a percentage expressing how likely the event is to occur.

Only when monitoring data collected during unrest show **linear behavior** eruptions can be predicted by a deterministic approach. The large eruptions of Mount St. Helens (USA) in 1980 and Pinatubo (Philippines) in 1991 were predicted days in advance. Linear behavior means an increase in the volcano's signals, and both the Mount St. Helens and Pinatubo unrest episodes showed this linear behavior.

LINEAR BEHAVIOR

When a system (such as a volcano) behaves in an expected way.

NON-LINEAR BEHAVIOR

When a system (such as a volcano) behaves in an unexpected way.

Unfortunately, the unrest that precedes many eruptions shows **non-linear behavior**: an increase in the intensity of the signals is followed by one or more decreases and finally by eruption. Under these erratic conditions, predicting an eruption in a deterministic way is impossible. Non-linear behavior shows us the complexity of the volcanic system, in which many processes, only some of which are detectable by monitoring, happen at the same time. Because of this complexity, forecasting eruptions is usually made using a probabilistic approach, in which the possibility for eruption is expressed as a percentage [2, 3]. This approach, which is also used in weather forecasting, more accurately accounts for the erratic behavior of volcanoes. So, to avoid errors, a wise volcanologist should

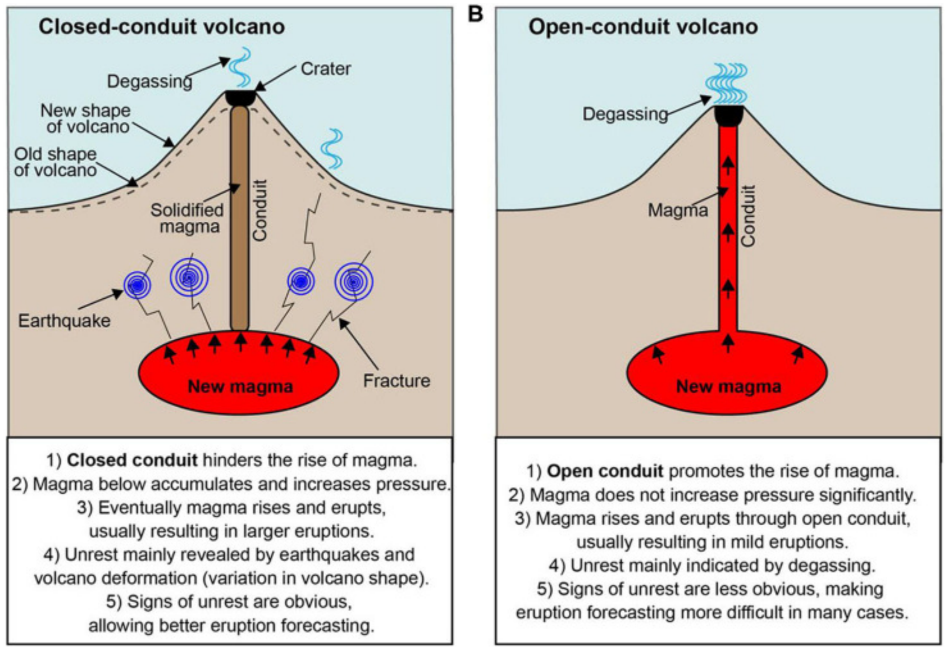

Figure 3

(A) Closed-conduit and **(B)** open-conduit volcanoes show different unrest behaviors. A single volcano can switch from closed- to open-conduit during its eruptive history.

forecast (probabilistic approach) rather than *predict* (deterministic approach) eruptions.

In recent decades, some eruptions have been successfully forecasted, while others have not been. Successful forecasting has led to successful evacuations, while inaccurate forecasting has led to evacuations followed by no eruption or to missed evacuations, when eruptions occur before people are evacuated. As a result, volcanology has experienced both successes and confidence in forecasting eruptions, as well as disasters and frustrations. Our capability to forecast eruptions is still limited, with ∼20% of eruptions accurately forecasted. Only moderate improvements have been made in the last few decades, despite the wide use and continual improvement of monitoring instruments [4].

VOLCANO TYPE AFFECTS FORECASTING

There are two types of volcanoes that affect the way eruptions are forecasted: closed-conduit volcanoes and open-conduit volcanoes (Figure 3). Closed-conduit volcanoes have solidified magma in the path through which the magma travels to the surface, which separates the molten magma from the Earth's surface. This causes magma to accumulate inside the volcano, which increases the pressure and breaks the surrounding rocks, generating fractures and earthquakes, and deforms the surface of the volcano. In closed-conduit volcanoes, unrest consists of seismicity, and surface deformation. Conversely, open-conduit volcanoes, which are less common, have molten magma filling the volcanic conduit, almost reaching the surface. The continuous supply of magma from inside the volcano prevents solidification of the conduit, causing frequent eruptions. In open-conduit volcanoes, magma does not accumulate inside the volcano, so pressure does not build up to fracture the surrounding rock or deform the volcano, although there is frequent degassing through the open conduit. This results in weaker unrest indicators. Therefore, given the stronger signals, forecasting eruptions is usually easier for closed-conduit volcanoes. Nevertheless, some well-monitored and frequently erupting open-conduit volcanoes may still provide enough data for a reliable forecast, such as Mt. Etna (Italy), whose eruptions are currently predicted with a 97% success rate. Since the global forecasting success rate for all volcanoes is ∼20%, the forecasting of Mt. Etna is extremely successful.

THE FUTURE

Volcanologists are constantly looking for new approaches to improve forecasting, by combining monitoring data with knowledge of volcanic processes. To identify the start of an eruption, recent studies focus on the appearance of specific monitoring signals that are directly related to the *rise* of magma, rather than its accumulation. This will help researchers to better forecast times when eruption is likely to happen soon. As some volcanoes have multiple eruptive craters scattered over wide areas, researchers also try to forecast the possible locations of future craters, to reduce the impact of eruptions in inhabited areas [1]. These efforts will certainly improve future eruption forecasting, providing more reliable probabilistic estimates and reducing the level of uncertainty or error. Nevertheless, we must remember that uncertainty is a part of any forecast, so future eruption forecasting will be similar to weather forecasting [5].

In summary, while forecasting eruptions is currently a difficult although not impossible task, future studies and research, as well as increased availability of monitoring data, will allow better understanding of how volcanoes work. This in turn will allow a more reliable eruption forecasting, reducing the adverse impact of volcanic activity on the population and environment.

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SUBMITTED: 12 November 2021; **ACCEPTED:** 01 March 2022;
PUBLISHED ONLINE: 28 March 2022.

EDITOR: Anna Regoutz, University College London, United Kingdom

SCIENCE MENTOR: Oscar Fernandez

CITATION: Acocella V (2022) How Scientists Forecast Volcanic Eruptions. Front. Young Minds 10:813910. doi: 10.3389/frym.2022.813910

CONFLICT OF INTEREST: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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We are two students from a bilingual Montessori elementary school (with a mixed-age class for 6–12 y) in Vienna, Austria. We are 8 (Tomas) and 9 (Armin) years old (3rd and 4th grade students). We like geography, biology, and math. We also like to learn about geology (volcanoes) and transportation (trains and airplanes). Together, we speak five languages (each of us at least 3 of these): German, English, Spanish, Italian, and Hungarian.

AUTHOR

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Valerio Acocella teaches different courses on volcanoes at the University of Roma Tre, Rome, Italy, where he is Professor. Attracted by their activity and power, he has been studying volcanoes in the five continents, from freezing Iceland to torrid Afar, for more than two decades. He had great fun climbing many volcanoes and meeting colleagues from very different countries, exchanging knowledge, and learning their habits and culture. His daughters have taken part of his time in the last 15 years, so Valerio is now traveling less and focusing on the active volcanoes

in Italy, which provide great opportunities to understand how volcanoes work; in particular, Valerio has coordinated large research projects on the major Italian volcanoes, as Etna and Campi Flegrei. The experience of Valerio on volcanoes is summarized in his recent book (*Volcano-Tectonic Processes*, Springer Editor, 570 pages). *acocella@uniroma3.it