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Isotopic Prediction of Eruption Volume at Continental Volcanoes

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Abstract

This is the final report of a one-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The objective of this project was to determine whether isotopic techniques can be used to assess the eruption potential and eruption volume of continental stratovolcanoes. Large-volume eruptions from stratovolcanoes pose significant hazards to population and infrastructure in many parts of the world. We are testing whether this technique will allow a short- to medium-term (decades to millennia) probabilistic hazard assessment of large-volume eruptions. If successful, the technique will be useful to countries or regions that must consider medium to long-term volcanic hazard to population centers and long-term surface and subsurface facilities (e.g., nuclear waste facilities). We have begun sample acquisition and isotopic measurements at two stratovolcanoes, Pico de Orizaba in eastern Mexico and Daisen in western Japan.

Background and Research Objectives

The volume of a volcanic eruption reflects the state of the underlying magmatic system, particularly the influx of new magma that inflates the system, causing failure of the magma chamber and eruption. At present, few techniques are available to assess the state and evolution of magma systems beneath stratovolcanoes during the past few hundred to several thousand years. This information is critical to forecasting eruptive volumes in a similar future time frame.

Magmas that supply volcanic eruptions originate from melting of the Earth's mantle and traverse the Earth's crust prior to eruption. During transit through the crust, mantle-derived magmas typically interact with and incorporate crustal wall rock. Neodymium (Nd) isotopes can be used to determine the relative contribution of mantle and crustal melts to a magma prior to eruption because the Nd isotopic compositions of crustal and mantle rocks are distinctively different, particularly in regions of ancient crust (Perry et al., 1993).

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Because of their high eruption frequency and proximity to human populations and facilities, stratovolcanoes are the most hazardous (in terms of damage to population and infrastructure) volcanoes on Earth. The correlation between eruption volume and Nd isotopic composition has recently been observed at Unzen, a stratovolcano in Japan (Chen et al., 1993). At Unzen, the three most voluminous dacite eruptions of the past 5000 years have more mantle-like Nd isotopic compositions, while the smallest volume dacite eruption of AD 1792 has a more crust-like Nd isotopic signature. These results indicate that Nd isotopic prediction of eruption volume is feasible for volcanoes that are active on the time scales of human concern.

Traditional volcanic monitoring techniques rely on either short-term monitoring (e.g., deformation-tilt, seismic monitoring) or statistical analysis of past volume-repose time relationships. The former methods provide little information for predicting volcanic eruptions beyond a few years in the future and the latter method has produced mixed results, particularly for long-lived volcanic systems that deviate from steady-state behavior over geologic time periods. The Nd isotopic prediction technique we are testing is the only technique that has the potential to give insight into the state of the deep magmatic system of a volcano decades to centuries before the onset of a large-volume eruption. The technique could thus be useful to countries or regions that must consider medium- to long-term hazard to population centers and long-term surface and subsurface facilities such as power plants and nuclear waste facilities.

Importance to LANL's Science and Technology Base and National R&D Needs

Development of the isotopic prediction model would enhance the Laboratory's competency in earth and environmental systems by adding to our knowledge of how volcanic systems work and what parameters control the volume of volcanic eruptions. This work complements DOE, national and international efforts in mitigating natural disasters.

Scientific Approach and Accomplishments

Any long-lived (>100,000 years) volcanic system requires thermal input in the form of magma recharge to thermally sustain the system. Our premise is that the volume and isotopic composition of magma in a crustal magma chamber reflects a thermal and mass balance between the rate of magma influx (recharge) and the rate of magma heat loss from conductive cooling and heat used to assimilate crustal wall rock. The inflation rate of a magmatic system (dM/dt) depends on the recharge rate, the assimilation rate (contributing the crustal component), and the crystallization rate (DePaolo et al., 1992; Perry et al., 1993; Chen et al., 1993). Assimilation and crystallization rates are very sensitive to the temperature of the magma, the initial temperature of the crust, the time since initial magmatic intrusion, and the heat transfer regime of the magma (conductive or convective). The recharge rate is controlled by mantle processes and can vary greatly with time. High recharge rates lead to inflation of the magma system, increasing the probability of large-volume eruptions, and will change the Nd isotopic composition of the system to more mantle-like values. Thus, a temporal trend to more mantle-like Nd isotopic compositions at a volcano indicates an increase in the magma recharge rate and a higher likelihood of voluminous eruptions. We anticipate using statistical and time-series techniques to evaluate the significance of the time-volume-isotopic trends. The isotopic measurements that provide the main data for this study are being performed at UC-Berkeley. Major and trace-element data were obtained at LANL to augment the isotopic data.

We began to test this model by assessing the eruptive history and Nd isotopic composition of eruptive products from two dormant stratovolcanoes, Pico de Orizaba in eastern Mexico and Daisen in western Japan. These volcanoes have been well characterized in terms of eruptive history, volume, and petrologic evolution. In the first stage of the study, we obtained material from representative large- and small-volume eruptions of the past few thousand years at each volcano to determine the extent of correlation between eruption volume and Nd isotopic composition.

We have made isotopic and geochemical measurements of representative small- and large-volume eruptive products from Pico de Orizaba and Daisen. Seven Nd isotopic measurements at Pico de Orizaba are complete and indicate a possible correlation between eruption volume and Nd isotopic composition (Figure 1). The isotopic measurements from Daisen are currently being completed at UC-Berkeley. While the first and third largest recent eruptions at Pico de Orizaba have the most mantle-like Nd isotopic values, consistent with our hypothesis, the second largest volume eruption has the least-mantle-like composition, which is inconsistent with our hypothesis. We are assessing whether this inconsistency points to other parameters of the magmatic system that may be important for determining eruption volume. The database at Daisen will be larger (~20 samples) and will allow us to better assess the relationship between eruption volume and isotopic composition. We plan to publish these data once data acquisition and assessment are complete.

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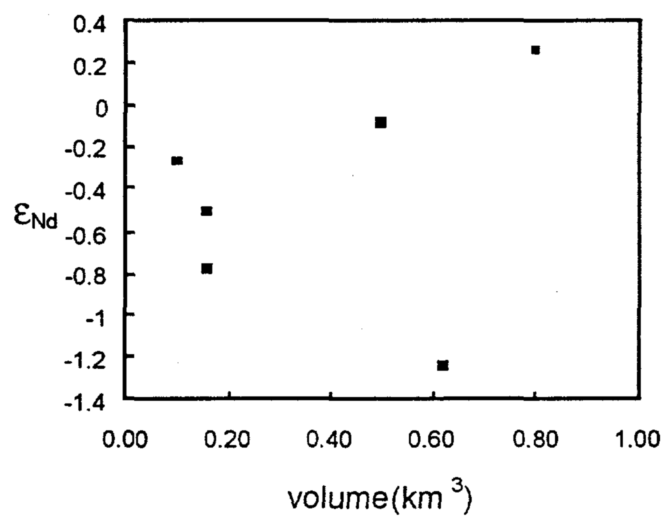

Figure 1. e_{Nd} versus volume for volcanic rocks of Pico de Orizaba volcano, eastern Mexico. These data show a possible correlation between eruption volume and isotopic composition that could be used to forecast the volume of future eruptions.