

Looking at volcanoes with cosmic-ray muons

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Penetrating particles created in the atmosphere reveal internal volcanic structures in much the same way that x rays image internal tissue and bones.

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Volcanic activity is not merely a subject for scientific study; it has profound implications for the people living in the areas near volcanoes. Of particular interest are when a volcano will erupt and what the nature of the eruption will be. Predicting the time of an eruption is hard. Nevertheless, by monitoring earthquakes and other signals, scientists can sometimes give local officials a few days' notice.

To foresee how an eruption could develop, scientists run computer models that require input information about the interior of the upper part of the volcano, the so-called edifice. Conventional techniques—based, for example, on the propagation of waves through Earth (seismology) or measurements of gravitational fields (gravimetry)—can be used to investigate internal structures such as magma chambers that lie deep under a volcano. However, their spatial resolution is no better than a few hundred meters, so the classic methods cannot identify possible conduits of eruptive material in the edifice. Over the past couple of decades, muon radiography—in short, muography—has emerged as a high-resolution imaging technique suitable for studying volcanoes. It is based on measurements of the absorption undergone by muons—penetrating particles generated by cosmic-ray interactions in the atmosphere—as they cross the edifice. Potentially, muography can reveal the density profile of a volcanic edifice with a resolution of tens of meters.

Shadows of volcanic structure

The principle behind muography is similar to that of x-ray radiography. When a doctor takes an x ray, a detector measures the intensity of radiation passing through a patient's body as a function of position. Since x-ray absorption depends on the thickness and density of the tissues traversed, the x ray itself is a shadowy image of the internal organs.

Matter strongly absorbs x rays, so x-ray radiology is limited to meter-scale applications. In muon radiography, the role of x rays is taken by muons. Undergoing the same interactions as electrons but 200 times heavier, muons are the most penetrating elementary particles except for neutrinos. High-energy muons can cross a few kilometers of rock, which suggests they might be a good tool for imaging large

geological structures. Of course, the muons will eventually get absorbed. To give an idea of how quickly, we note that muon flux is attenuated by more than a factor of 10 when a target increases in thickness from 1 to 2 km.

Cosmic rays—energetic particles originating far beyond Earth—interact with Earth's atmosphere and provide an abundant natural source of high-energy muons. In a muographic study, a researcher places a muon detector within a kilometer or so of the object under investigation. The detector measures the number of muons traversing the object horizontally as a function of direction and so reveals the object's internal structure.

Because muon detectors can scrutinize substructures in a target that is a sizable distance away, they are sometimes called muon telescopes—a reference to their optical counterparts. The long-distance gaze of the detectors also means that scientists using them don't need to access the summit of the volcanoes they study. A typical muon telescope has a detection area of 1 m² and takes a couple of weeks to image a small edifice that is a few hundred meters across; in a few months it can obtain a density profile for a 1-km thick structure. For large, active volcanoes, employing a typical, modest-sized telescope for the time needed to acquire useful data may not be feasible. In that case, if financial resources allow, researchers can monitor changes in internal structure with large-surface-area detectors or with several small detectors working simultaneously.

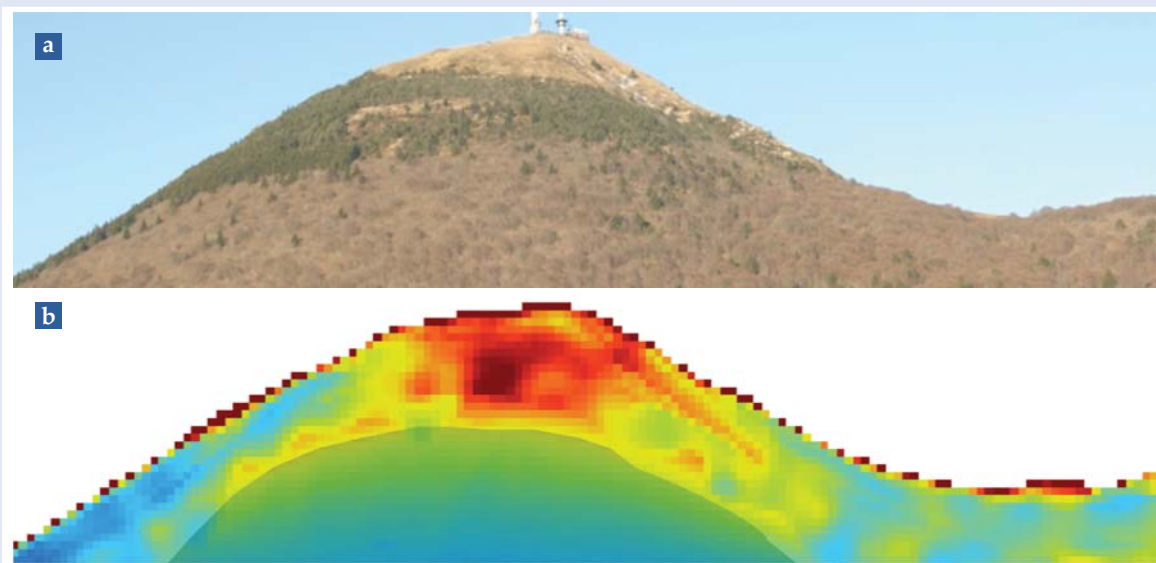
In conjunction with results from conventional techniques, muography data might help in identifying an actual structure from the multiple possibilities that generally arise when investigators try to infer the internal structure of an edifice from classic observations. Work is in progress to find the optimal way of analyzing the muon data and, even more important, to understand how to combine muon-based and conventional measurements.

History, current work, and prospects

Scientists have imagined various potential applications for the high-energy muons generated from cosmic rays. The first was to archaeology. In 1967 a team led by physicist Luis Alvarez installed a muon telescope in the Belzoni chamber deep inside the pyramid of Chephren in Egypt. It was looking for hidden chambers above Belzoni but found nothing.

The application of muon radiography to volcanoes was pioneered in the mid 1990s by Kanetada Nagamine and further developed by Hiroyuki Tanaka and collaborators. Their work not only suggested new ways to study the internal structure of volcanoes, it also stimulated interest in developing other applications.

In 1995 Nagamine placed a muon telescope with a detector area of 1.0 m² about 1 km from the top of Mount Tsukuba in Ibaraki, Japan. A reconstruction of muon tracks enabled him to determine absorption along different ray paths through the mountain and consequently to map the average density of the rock traversed. Subsequently, Tanaka



Images of Puy de Dôme, located in the Massif Central region in south-central France. **(a)** This photograph of the dormant volcano's summit shows a section about 400 m high. **(b)** The muon opacity shown here (red is most opaque; blue, least), from the Tomuvol collaboration's preliminary radiography measurements, is closely related to the density of volcanic material. A dense core is clearly visible in the upper part of the cone. The featureless region at the bottom of the cone was inaccessible to Tomuvol's small detector.

and colleagues investigated the lava dome of Mount Iwodake on Japan's Satsuma-Iwojima island and the so-called parasitic cone of Mount Usu in Hokkaidō.

In some cases interesting internal structures have been observed and correlated by conventional measurement techniques. One example is inside the Puy de Dôme in France, shown in panel a of the figure. That dormant volcano is currently being studied by the Tomuvol collaboration with a detector technology originally developed for particle physics. About a year ago, after taking two weeks of data with a 1-m² detector, the Tomuvol group discovered a very dense and compact structure below the summit (see panel b). The observation was confirmed a few months later by gravimetric measurements. The group is now working toward deploying its muon telescope on active volcanoes. The French Diaphane collaboration has already used muography to peek inside an active volcano, La Soufrière of Guadeloupe. The highly heterogeneous density structure that the group observed was also confirmed with conventional techniques.

The Mu-Ray project is currently working to study two active Italian volcanoes that provide real challenges to muography: Mounts Vesuvius and Stromboli. Because of the violent nature of its eruptions and the 600 000 people living nearby, Vesuvius carries a terrifying potential risk. Stromboli is a particularly interesting volcano. It has an essentially open conduit, and gas bubbles, rising in the magma, result in small periodic explosions—so-called strombolian activity.

Vesuvius and Stromboli are large. To image them, muons would need to pass through more than 2 km of rock. Given the significant attenuation of muon flux, successfully applying muography would require a large detector area and impressive background reduction. To that end, the Mu-Ray collaboration is testing a prototype based on silicon photomultipliers, which transform the extremely faint light generated by muons crossing a plastic material into an electric signal. The photomultipliers are rugged, consume little power, and are sensitive enough to detect a single photon—properties that make them well suited to muon radiography applications.

Since its application to the search for hidden chambers in the pyramid of Chephren, muon radiography has profited from the development of detection techniques for particle physics and advances in data-analysis methods and computing. A few decades ago the southeastern part of the Belzoni chamber was practically filled with spark chambers. Today a typical muon telescope has a volume of 1 m³, has a mass of a few hundred kilos, can be easily transported, and consumes so little electricity that it can be used where electric power comes only from solar panels or other alternative sources. Moreover, muography measurements are continuous and, since they can be remotely controlled, provide ongoing information about changes in a volcano's inner structure without endangering scientists. Much work remains to be done, but the technique has remarkable potential as a tool for reducing the hazards associated with volcanoes.

Additional resources

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