

## Cosmic-ray muon radiography of volcanoes

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Radiography with x-rays is commonly used in both medical and industrial applications. When a beam of radiation is transmitted through any heterogeneous object, it is differentially absorbed, depending upon the varying thickness and density of this object. The image registered on a photographic film adjacent to the specimen under examination constitutes a shadowgraph or radiograph of its interior. Industrial radiography has been used for detection of internal physical imperfections such as voids, cracks, flaws, and porosities. It is frequently used for visualization of inaccessible internal parts in order to check their location or condition. This technique can be applied to view volcanoes except for substituting penetrating muons to serve in place of X-rays. We have developed a novel radiographic imaging method to survey the inhomogeneous structure of the crust. As an example, we performed measurements at Mt. Asama and Mt. Usu volcanoes, and studied the feasibility of using an azimuthally isotropic flux of cosmic-ray muons in the energy range up to a few TeV. The principle of the technique is that by measuring muon absorption along different nearly horizontal paths through a solid body, one can deduce the density distribution in the interior of the object. A muon detector comprising of emulsion films were installed at the foot of volcanoes. Muon tracks within emulsion layers in the detector were analyzed by 3d image processing to determine the level of energy absorption along different ray paths through the summit crater region. A typical angular resolution of the muon detector of 10 milliradians (mrad) corresponds to a spatial resolution of 10 m at a distance of 1 km. The measurements would be ideal for studying the shallow structure of the crust at sites which cannot be well resolved because of their strong structural heterogeneity and potential difficulty to be accessed, and which therefore cannot have their structure determined by conventional electromagnetic or seismic techniques. The present method can also provide three dimensional images of the subsurface by making measurements from two or more different points. In this work, we have radiographically imaged a few hundred meters below the crater floor of Mt. Asama, Japan, and have detected a dense region, which corresponds to the position and shape of a lava mound created during the last eruption. Right below the lava mound we found a low density region that suggests a drain-back-induced porous conduit. The density contrast was resolved with a precision of 1-3%. In Mt. Usu, We successfully imaged the conduit shape and determined a conduit diameter of  $102 \pm 15$  m, assuming the observed high absorption region beneath the dome is localized in the vent area. This method provides a resolution of the shallow density structure that is significantly higher than is possible with conventional geophysical measurements.