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Looking through Volcanoes with Cosmic-Ray Muons

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Muons from cosmic rays are continually shining upon us. Cosmic-ray muons with the highest energies penetrate large solid objects but are absorbed in them, so that the rate of muons passing through an object is reduced. This effect can be used as the basis of a technology for determining the density legth (density times length) probing an internal-structure and its time-dependent movement of matter in the interior of large objects, both natural (i.e. a volcano) and artificial (i.e. an industrial machinery).

We have found that the use of near-horizontal cosmic-ray muons removes many of the problems of the earlier attempts. Near-horizontal muons can penetrate objects of sizes between 100 meters and 1 kilometer in rock-mountain, and the apparatus is much simpler as there is no need to dig a hole under the object. Difficulties include the low intensity of near-horizontal muons and a large background from a soft-component cosmic-ray of electrons and gamma rays.

By using the detection system, as seen in Fig. 1, comprised of two plastic counters, each of which is segmented in both x and y directions, with Fe plates placed in-between, we have successfully overcome the difficulties; 1) by comparing muon signal from objective (Forward) and muon signal from sky or nothing (Backward) for each path of the muon, sound detection and analysis was realized for the weak-intensity near-horizontal muon; 2) by eliminating multipticity events detected at the second counter, background was almost completely removed.

We have studied two active volcanoes, Mt. Asama and Mt. West Iwate in Japan, by using this detection system with a sensitive area of 2 m x 1 m.

During the period January-May 2002, by detecting the near-horizontal muon through the summit region of Mt. Asama, the crater part was detected from outside and was found to be vacant, corresponding to the magma occupancy in the crater being less than 10 vol % as seen in Fig.2; we are planning to continue the same measurement to determine if there has been any change after the Summer 2004 eruption.

During the period of May 2002 to May 2003, the density of the upper region of the active part of Mt. Kurokura of Mt. West Iwate was determined, and compared favorably with gravimetric data of gravitational-constant measurement. In addition, some indication was obtained for a time-dependent change in density in the active part, possibly reflecting a movement of water inside the volcano.

By expanding the scale of the detection system, this method may eventually lead to accurate prediction of volcanic eruptions and other geological events. As a guide for a planning of measurement one can consider the following situation. Suppose we have a volcanic mountain with 500 m diameter at the distance of 1000 m from the detection system for the near-horizontal cosmic-ray muon with a sensitive area of 20 m $\times$ 1 m. Then, the density length can be determined with 3 % accuracy in 3 days; finding e.g. a 30 % density-change in 50 m diameter magma-channel. By using more than two detection system, a tomographic measurement can be carried out.

Recently the same detection system was used for an industrial application, namely, to probe the inner structure and its time-dependent change of a large-scale machinery. Successful measurement was carried out for one of the world's largest blast furnace, in Japan. We were able to measure the thickness of the brick bottom-layer with an accuracy of $\pm$ 5 cm after 50 days, and the density at various locations in the iron load could with an accuracy of 0.2 gr/cm^3. This permits monitoring of a time-dependent change in the interior of the blast furnace.