論文の内容の要旨

Development of multi-directional muography
（多方向ミュオグラフィの開発）

氏名　長原　翔伍

Muography is an imaging technique to measure the density of objects by using cosmic-ray muons. This is one of the best observation methods for probing the structure of objects of about 1000m in size. Many volcanic structure surveys have been carried out using this technique (Tanaka et al., 2007a; 2007b; Oláh et al., 2018; Lesparre et al., 2012). This can also be used to obtain a three-dimensional density structure by observing the same volcano from multiple directions. However, the previous studies have been limited to three directions at most (Rosas-Carbajal et al., 2017), and we have not yet been able to perform 3D density structure survey using muographic observations from multiple directions.

The reason why multi-directional muography has not been done is the following issues.

A) Secure enough detectors to observe in multiple directions.
B) Mass production of detectors and establishment of operation methods.
C) Fast processing from observation data to muon tracks.
D) Development of methods for 3-D density reconstruction.

For (A), Morishima et al. (2017b) have already realized muographic observations using

a large number of nuclear emulsion films. For (C), Yoshimoto et al. (2017) and Hamada et al. (2012) have developed a fast processing technique for nuclear emulsion observation data, but it had to be optimized for muography. For (D), there is an analysis method by Nishiyama et al. (2014a), but there were some difficulties in performing high-resolution 3D density reconstruction with this method.

In this paper, we have developed (B) and improved (C) and (D). We also conducted a demonstrative observation at Mt. Omuro-yama in Izu Peninsula, Japan.

First, we developed a detector suitable for multi-directional muography. The features of this detector are as follows.

(a) Easy to handle many emulsion films and lead plates for noise reduction.
(b) A special spring plate was developed to provide uniform pressure to reduce the thermal expansion of the film.
(c) Insulation is used to protect the emulsion film from high temperature.

In addition, FOG (Fiber-Optic Gyroscope) was used to measure the direction and attitude of the detector at any location for field operations.

Second, the process of obtaining muon tracks from observed data was improved for muography. In the previous analysis method, the track data of cosmic rays other than muons are mixed into the track data. In this study, we developed a method to select muon tracks from them. Also we confirmed the noise particle rejection capability using simulation. As a result, low-energy particles below 1 GeV, which were shown in Nishiyama et al. (2014b), could be removed. We also developed a method to evaluate variation of the efficiency according to the detector geometry.

Third, we have improved the 3D density reconstruction method using muography. Specifically, we improved the method to reflect the viewing angle of the observed data.

A demonstrative observation was performed at Mt. Omuro-yama to show the possibility of multi-directional muography. Observations were made in three locations in 2018 and eight locations in 2019. First, the muon counts in free sky region were compared to simulations to evaluate whether the observational data were properly acquired. As a result, it was found that the observed muon number was about 10% less than the simulation. The ratio of the observed muon counts to the simulated muon counts was used as the calibration value. The calibration values were applied to obtain a two-dimensional muographic image. We applied our improved 3D density reconstruction method to the observed muon counts.

The error and uncertainty of the obtained density distribution and the appropriateness of the model parameters were evaluated. The resolution was also evaluated by simulation.

For the model parameters, we considered the correlation length l and a priori error of the density σ_ρ in Nishiyama et al. (2014). For l, we constrained the lower limit to 70m based on the consideration of the amount of information in the data and the degree of freedom of the fitting parameters. For σ_ρ, we excluded the cases with densities of less than 0.5 $(\mathrm{g/cm^3})$ or greater than 3.0 $(\mathrm{g/cm^3})$, which are unrealistic volcanic densities. As a result, $\sigma_\rho < 0.5$ $(\mathrm{g/cm^3})$ was selected. We also excluded $\sigma_\rho = 0.1\,(\mathrm{g/cm^3})$ because it was too restrictive and 3D density structure could not be reconstructed. We also confirmed that there was no significant effect on the reconstruction results between l = 70 m and 100 m. We confirmed that between $\sigma_\rho = 0.2(\mathrm{g/cm^3})$ and $0.4(\mathrm{g/cm^3})$, the density contrast changes but the structure does not change.

Next, we evaluated the error of the density distribution. Three types of errors were evaluated. The first was to determine the propagation of the error in the observed data, which was determined by the posterior variance matrix in the inversion. Second, we evaluated the effect of the initial density assumed in the inversion. Since the initial density was the value of the bulk density of the mountain obtained from muography data, the error of the 3D reconstruction result coming from the initial density was estimated. Third, we evaluated the stability of the data by selecting the data to be used. We performed 3D density reconstruction excluding data from one observation point and compared it to the case where data from all observation points were used. As a result, it was found that when an observation point was removed, the area near the point tended to become denser. The sum of the squares of the three errors was taken as the variance value of the density error.

In order to evaluate the spatial resolution of the obtained density structures, we performed simulations assuming two types of structures. The first is the case where a 100m diameter cylinder exists just below the crater. The second is the case where a plate-like heterogeneity exists from the west to the crater. The reconstruction result appears to be twice as thick and tends to be larger in the center of the mountain.

Based on the obtained 3D density reconstruction results, taking into account the error and resolution estimation, the internal structure of Omuro-yama was interpreted by comparing it with previous studies and high-precision topographic maps. The structure confirmed by the results of muography is as follows. A high-density region existed in the central part of the mountain body, and the high-density region extended to the west. A high-density region was also found in the south-southeast.

From the above, we have constructed a tentative story of the formation process of

Omuro-yama, mainly in its final stages, together with the results of topographic readings. First, when most of the mountain body was formed and a lava lake was formed in the summit crater, the expansion of the mountain body formed a dike that went in three directions from the conduit. Westward dike flowed seeping out from the west side of the mountain. The south-southeastward dike erupted a small crater on the south mountainside. Subsequently, most of the lava lake in the summit crater drained back. After the drained back, the area around the conduit remained hot and the welding progressed to form the high density region in the center of the mountain.

With this research, we established the detectors, installation techniques, and analysis methods necessary for multi-directional muographic observations. We will increase the number of observation directions by conducting similar observations in the very near future, and 3D density reconstruction with higher spatial resolution and precision will become possible.