Magnetization Structure of the Unzen Volcano Determined from Blimp-Borne Magnetic Survey Data

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(Received July 21, 1994; Revised November 28, 1994; Accepted December 2, 1994)

We have attempted a blimp-borne magnetic survey over the Unzen Volcano which has been erupting since November, 1990. The first attempt, made in January, 1992, was unsuccessful, but the second one in March, 1992 was partly successful, yielding the distribution of the geomagnetic total intensity at an altitude of about 1,500 m. These total intensity data could be interpreted in terms of inhomogeneous magnetizations of rocks forming respective mountains of the Unzen Volcano. The east of Mt. Fugen, which is the site of current lava extrusion, shows a magnetization of 2~3 A/m. This result would be an important piece of information for a study of volcanomagnetic effect, in particular in constructing a thermal demagnetization model.

1. Introduction

Volcanomagnetic effects have been studied from time to time (e.g. Zlotnicki and Le Mouél, 1988; Yukutake *et al.*, 1990; Tanaka, 1993). In most cases, observations of the geomagnetic field were made at fixed locations distributed around a volcano. Such an observation method certainly has a merit; that is, capability of detecting slight time changes. Its demerit may be incapability of grasping a spatial distribution of changes, since spatial as well as temporal information is important in interpreting the magnetic data in relation to volcanic activity.

One possible means of monitoring the spatial distribution of temporal changes in the geomagnetic field associated with volcanic activity is a repeated aeromagnetic survey at low altitude. It is dangerous, however, to make such a magnetic survey with a manned vehicle over a volcano at an active stage. In this respect, we have already attempted to use a small radio-controlled blimp for a low-altitude aeromagnetic survey (Makino *et al.*, 1991). So far, however, we have been unable to make a blimp-borne magnetic survey over a volcano, where a severe problem arises; for example, pressure difference between the blimp base and the summit area of a volcano.

We first attempted a blimp-borne magnetic survey in January, 1992 over the Unzen Volcano, which is located in the western part of Kyushu Island, Southwest Japan. The volcano started to erupt on 17 November 1990 and the eruption has continued until now (e.g. Ohta *et al.*, 1992). Several domes have extruded rather intermittently, with the volume rate of lava extrusion amounting to the order of 10^5 m³/day (Nakada and Fujii, 1993). Our first attempt suffered greatly from the above problem, resulting in a complete failure; the blimp burst on its way to the summit area.

In our second attempt, we decided to reduce the payload and instead of GPS measurements of sensor position, we made transit observations from the Earth's surface to locate the blimp

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positions during its flight. Our primary purpose of this attempt was to examine whether it is possible at present to make a precise low-altitude aeromagnetic survey over an erupting volcano. Without GPS, however, this is almost impossible and hence we directed our aim toward a study of the magnetic structure of the Unzen Volcano.

Low-altitude magnetic data over a volcano enable us to study a fine magnetic structure of the volcano. In contrast, a high-altitude aeromagnetic survey provides information on a structure of wider scale, and in fact, Nakatsuka (1994) found a characteristic graben structure beneath the Unzen Volcano area, by analyzing aeromagnetic data at the altitude of 7,500 feet. Determination of a fine structure is useful for a volcanomagnetic study based on observations at some fixed sites on volcano flanks, as we will discuss later.

2. Data

Our second attempt of making a blimp-borne magnetic survey over the Unzen Volcano was made on March 12, 1992. Figure 1 shows the topography around the Unzen Volcano. A proton precession magnetometer loaded on a radio-controlled blimp measured the geomagnetic total intensity at every five seconds at the altitude of about 1,500 m above the sea level. The flight-path, shown in Fig. 2, was determined by transit measurements at the summits of Mt. Kunimi and Mt. Myoken, and the second parking place of the Nita pass. Figure 2, corresponding to the shaded area in Fig. 1, also shows the distribution of geomagnetic total intensity yielded from the mesh data, which were derived for the mesh size of 62.5 m from the measured data along the flight-path. The contour interval is 50 nT. The total intensity distribution seems to be characterized by a pair of positive and negative anomalies, reflecting mostly the magnetization structure of Mt. Fugen.

3. Interpretation

3.1 Model

Let us consider a prism of horizontal size of 62.5 m (both in the north-south and the east-west directions) and represent the volcano body by a number of such prisms with their top surfaces corresponding to the topography and their bottom surfaces to the sea level. We assume that the

Fig. 1. Topography around the Unzen Volcano. The blimp-borne magnetic survey was made in the shaded area.

Fig. 2. Flight-path of the radio-controlled blimp and the distribution of the geomagnetic total intensity derived from the measured data along the flight-path at the altitude of about 1,500 m. Contour intervals are given in units of 50 nT.

magnetization is uniform within adjacent four prisms (2×2) and the direction of magnetization of all the prisms is the same as that of the present magnetic field of the Earth (inclination 46.2° and declination -5.9°). Magnetization intensities of 140 (14×10) blocks and one uniform magnetization region surrounding them are now unknown quantities. The assumption of uniform magnetization for the outer region surrounding the 140 blocks may not be realistic but the central target area would not be affected much by this assumption.

3.2 Inversion

We adopt a linear least-squares inversion with a smoothness constraint in order to determine a model $\mathbf{m}$ (magnetization structure) from the observed data $\mathbf{d}$ (geomagnetic total intensity). Here we must minimize a functional U ,

$$U = \|W\mathbf{d} - Wf(\mathbf{m})\|^2 + \alpha^2 \|C\mathbf{m}\|^2, \quad (1)$$

where W is a weighting matrix, $f(\mathbf{m})$ is a function representing the model, α is a smoothing parameter, and C is a roughening matrix. The first and the second terms on the right-hand-side denote the data misfit and the model roughness, respectively, and the smoothing parameter, α , controls a trade-off between them. In this study, the matrix C represents the second finite difference of the model parameters between adjacent blocks; that is, variations of magnetization from one block to another are to be made smooth.

In searching for an optimum value of α , we rely on a statistical approach, the *ABIC* minimization. An information criterion, *ABIC*, was derived in association with the maximum Bayesian likelihood (Akaike, 1980),

$$ABIC = -2 \log(\max L(\mathbf{m}|\mathbf{d})) + 2(\text{number of hyperparameters}), \quad (2)$$

where $L(\mathbf{m}|\mathbf{d})$ is a Bayesian likelihood. The smoothing parameter α is the only hyperparameter here. A model which minimizes *ABIC* is supposed to be the most suitable one. *ABIC*, which is

a function of the smoothing parameter α , is given as

$$ABIC(\alpha) = N \log \left(2\pi \frac{U}{N} \right) - \log |\alpha^2 C^T C| + \log |(Wf(\mathbf{m}))^T (Wf(\mathbf{m})) + \alpha^2 C^T C| + N + 2, \quad (3)$$

where N is the number of observed data and $|\cdot|$ denotes a determinant of a matrix. The *ABIC* minimization method has been applied to linear problems (e.g. Akaike, 1980; Murata, 1990) and also to non-linear problems (e.g. Uchida, 1993a, b).

4. Results

Figure 3 shows a U-rms misfit defined by $\{U/(N-1)\}^{1/2}$ (Uchida, 1993a) and *ABIC* as a function of the smoothing parameter α . It turns out that *ABIC* is minimized when $\alpha = 0.02$; this value can be considered an optimum value in the *ABIC* minimization method.

The magnetization structure for $\alpha = 0.02$ is shown in Fig. 4(a). Magnetization values less than 0 A/m are shown by white, those between 0 A/m and 5 A/m by gradual gray scales, and those more than 5 A/m by black. Figure 4(b) show the difference between the geomagnetic total intensity values shown in Fig. 2 and those calculated from the magnetization structure shown in Fig. 4(a).

The magnetization structure derived for the smoothing parameter $\alpha = 0.02$ should be optimum in principle, but it is unrealistic actually. The general differences are in fact small as shown in Fig. 4(b), but magnetization variations are not smooth. Moreover, the maximum and the minimum values of magnetization are 12.9 A/m and -7.7 A/m, respectively, which deviate greatly from the values of magnetization of volcanic rocks of the Unzen Volcano measured by Ozima *et al.* (1992). We ascribe such an unexpected peculiar result to the data themselves, which include errors due to insufficient determination of the blimp position.

In order to put more emphasis on consistency with the measurements of Ozima *et al.* (1992), we increased α values and enhanced the smoothness in magnetization variations. Figure 5(a) shows the result for $\alpha = 0.2$. Contrary to our expectation, differences are not much larger, as shown in Fig. 5(b). The strong magnetization zone, about 4 A/m, extends from the east of Mt. Kunimi to the southeast direction. The northern and the southeastern portions of Mt. Myoken show a weak negative magnetization ($-0.97 \sim -0.04$ A/m). The maximum and the minimum

Fig. 3. U-rms misfit and *ABIC* as functions of the smoothing parameter α .

Fig. 4. (a) Magnetization structure around the Unzen Volcano for $\alpha = 0.02$ and (b) the distribution of the difference between the observed total intensity values and those calculated for the magnetization structure. Solid contours indicate positive values, whereas dashed contours indicate negative values.

Fig. 5. (a) Magnetization structure around the Unzen Volcano for $\alpha = 0.2$ and (b) the distribution of the difference between the observed total intensity values and those calculated for the magnetization structure. Solid contours indicate positive values, whereas dashed contours indicate negative values.

values of magnetization are 5.49 A/m and -0.97 A/m, respectively, which can now be regarded as consistent with the measurements of Ozima *et al.* (1992).

5. Discussion

Although positioning data are not very accurate and flight passes are not sufficient to cover all the mountains of the Unzen Volcano, we could partly estimate its magnetization structure, as

shown in Fig. 5(a). We now discuss on some notable features of the magnetization structure with particular attention to an inhomogeneous structure.

We first point out that Mt. Myoken is very weakly magnetized, whereas magnetizations of the other two mountains, Mt. Kunimi and Mt. Fugen, are fairly strong, amounting to 4 A/m or so. The east of Mt. Fugen would be of great interest, because it is the currently erupting place, and some observation sites for continuous measurements of the geomagnetic total intensity are located there. Tanaka (1992) proposed a model to interpret a marked change in the total intensity exceeding 10 nT. In his model, a demagnetized zone develops as a result of ejection of host rocks, as volcanic ash, assuming that the magnetization of host rocks amounts to 3 A/m. This assumed value of magnetization is in good agreement with the magnetization in the east of Mt. Fugen, as shown in Fig. 5(a).

Ozima *et al.* (1992) found that rocks from different eruption events possessed considerably different magnetization values. For instance, rock samples from the 1663 eruption lava shows 3 A/m, whereas those from the 1792 eruption lava shows 7 A/m. Some samples from the 1991–1992 eruption lava show a weak magnetization, 1 A/m or so (M. Ozima, personal communication, 1992). These rocks have similar bulk chemical compositions. The differences in magnetic properties reflect different oxygen fugacity in rocks during cooling of the rocks (Ozima *et al.*, 1992). The inhomogeneous magnetization structure of the Unzen Volcano is thus a result of extrusion of lava with a magnetic property varying from one eruption to another. This information is of some importance in discussing the mechanism of eruption, although it is beyond the scope of this paper.

We thank J. Hirabayashi for encouraging us throughout the magnetic survey. We also thank H. Watanabe for his useful comments. This study was supported by the Ministry of Education, Science and Culture.

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