High-Resolution, Low-Altitude Helicopter-Borne Aeromagnetic Survey over Unzen Volcano, Kyushu, Japan

A. Okubo[1], Y. Tanaka[2], M. Utsugi[2], N. Kitada[2], H. Shimizu[3], and T. Matsushima[3]

[1]Disaster Prevention Research Institute, Kyoto University,

[2]Institute for Geothermal Sciences Graduate School of Science, Kyoto University,

[3]Institute of Seismology and Volcanology, Faculty of Science, Kyushu University.

1. Abstract

On September 18, 2002, we conducted helicopter-borne magnetic surveys over Unzen Volcano, one of the active volcanoes on Kyushu island, Japan. Recently, the volcano repeatedly erupted dacite lava, forming an active lava dome complex in the summit area of Fugendake during the period 1990-1995.

During and after the eruption, several aeromagnetic survey flights over Unzen volcano were conducted and the aeromagnetic anomalies were analyzed within the flight area. However, precise magnetization intensity distributions have not been obtained because of problems in the accuracy of data positioning. The present study overcomes such problems by conducting aeromagnetic surveys during two different, high-resolution, low-altitude flights, using for the first time spiral trajectories.

The resultant magnetization intensity map shows a good agreement with the geologic features and topography on the volcano, especially the hydrothermal alteration zone and the collapsed pyroclastic deposits. In addition, even if the surfaces are covered by lavas, the magnetization intensities show various values for each eruption event. It may be considered that the differences in magnetic properties reflect different oxygen fugacity in rocks during their cooling time period. Besides, magnetization low locally distributed on Heisei-Shinzan suggests that the Heisei lava produced by the 1991-1995 eruption has not yet cooled.

2. Surveys and Data Reduction

The helicopter-borne aeromagnetic surveys were operated with the assistance of Nagasaki Prefecture on September 18, 2002. The two flight surveys covered the summit area of Unzen volcano. In this survey, we conducted spiral trajectories, keeping at low altitude and a constant altitude above the ground, this is because it is difficult to carry out traditional trackline path for the topographic relief filled with ups and downs in this survey area. One is at an average altitude of 320m (*FlightH*) above the ground, the other is at 180m (*FlightL*). The standard deviations of altitude are 64.6m and 57.7m, respectively. Fig.1 shows both the flight-paths and flight-altitudes above the ground for the two surveys. Geomagnetic total field was recorded by an optical pumping magnetometer (GEOMETRICS) installed in the sensor bird and an Overhauser proton magnetometer (GEM) suspended with a wire of 20 m long under the airframe. The sampling intervals of these magnetometers are 0.1 sec and 0.5 sec, respectively. However, we did not apply the data recorded by the GEM the sensor bird to this analysis, because the data tended to fluctuate along track direction. While real time navigation was achieved by a portable GPS receiver with a PC monitor, precise positioning data of the sensor bird was obtained by a differential GPS technique with a time resolution of 1.0 sec. The equipment utilized and the specifications in these surveys are summarized in Table 1. In this study, we used the magnetic field by the GEOMETRICS sensor and analysised by resampling the data to 1.0 sec to coincide with the GPS data.

Diurnal magnetic variations of extra-terrestrial origin were removed by subtracting the total field data recorded at a temporal station nearby and the International Geomagnetic Reference Field (IGRF 2000) was subtracted from the data in order to remove the effect of Earth's internal deep source.

3.Method

After the correction of diurnal magnetic variations and IGRF residuals, the average terrain magnetization was estimated using a statistical correlation method (Grauch, 1987) in order to eliminate the effect of topography. In the terrain effect, the magnetization intensity and direction of each prism was assumed to be a constant value, and to be magnetized with a 46.5 degrees inclination and 6 degrees W declination, identical to the direction of the Earth's present magnetic field, respectively. The averaged magnetization of the survey area was derived to be 3.1A/m. However, there still remain a large number of magnetic anomalies with relatively short wavelengths. This implies that large distortations of the magnetic anomalies on flight altitude are caused, because the intervals between adjacent observation points are irregular with the observation noise. Therefore, in order to eliminate the large distortions and noise, we get the upward continued applying this corrected anomalies to the equivalent anomaly method (Makino *et al.* (1993)).The reduction surfaces, to which magnetic anomalies were attributed, were selected so that the surfaces are 500m higher than the average altitude (above the ground) of the actual observation, respectively.

Then, We applied the magnetization intensity mapping method to the anomalies of Fig. 2 employing the CG method with the following configuration of assumed prismatic bodies:

1) We divided the crust with the 150m by 150m in horizontal extent, whose block size take topographic relief of 50m-grid into consideration, and the vertical extent is from 500m under sea level.

2) The prismatic bodies are arranged to cover an area 1.8km beyond the survey area in order to avoid edge effects. In this study we have n=6498 for the two data of Fig.2 and m=6400 for the unknown parameter. The inversion carried out for *Flight_H* and *Flight_L*, simultaneously. The results of the joint inversion are shown in Fig.3. Iterations were stopped after 20 trials when the standard deviations of differences between the observed and calculated fields were 29.9nT and 34.7nT for *Flight_H* and *Flight_L*, respectively.

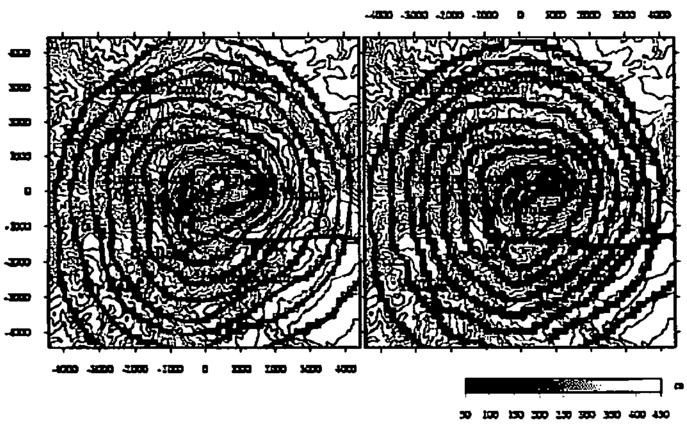

Fig.1. The spiral lines indicate trackline paths of the aeromagnetic surveys and the color contours shows the observed altitude above the ground for *Flight_H* and *Flight_L*, respectively. Topographic contour interval is 50m.

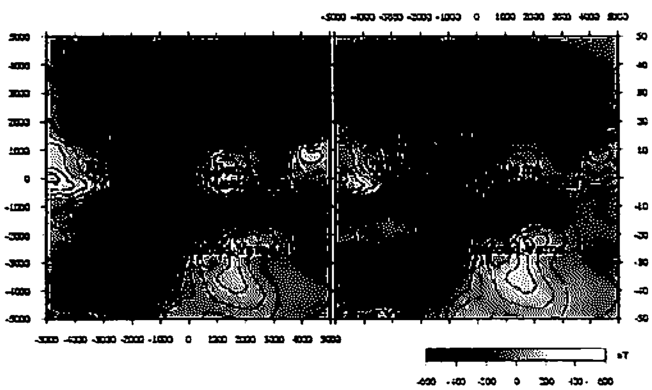

Fig.2. Upward continued magnetic anomalies to the surface, which is 500m higher than the average altitude of the actual observations for both *Flight_H* and *Flight_L*. The contour intervals in each case are of 50nT.

4. Results and Discussion

We discuss some characteristics of the distribution of the magnetization intensity, as shown in Fig.3, and its relation to the geology and topography of Unzen Volcano in order to be affected much by the earth surface. Because of the lack of detailed resolution of the obtained magnetization intensity mapping, we will discuss the general relationships. Table 2 summarizes some characteristic correlations between the magnetization intensity, geology and topography.

(1) On Heisei-Shinzan (Dome), a magnetization low of <0.5A/m (A) is locally distributed. This suggests that the Heisei lava produced by the 1991-1995 eruption has not yet cooled. In addition, magnetization lows of <0.5A/m predominate in an area south of the Dome (B). This region corresponds to block-and-ash flows and talus deposits from 1991-95.

(2) Magnetization highs of 4.0 to 7.5A/m are distributed in 2km nothern of Dome (C), near the summit of Iwatoko-Yama (D), extending from W to E in southern of a center axis of Akamatsu-Dani valley (E), and at Ya-Dake (F). These areas of magnetization highs correspond to lava flows of the Older Unzen volcano. In addition, magnetization highs of 5 to 6.5 A/m predominate around Fugendake (G), which correspond to dacite lavas of Fugendake, and the area of magnetization highs (7.0A/m) of 2km northeastern of Dome (H) corresponds to the Senbongi lava. In contrast, magnetization lows predominate in other lavas of Unzen volcano. Magnetization lows of 1.5A/m extend from the Myoken-Dake lava (I) to the No-Dake lava (J). The results of the aeromagnetic survey of Mogi *et al.* (1995) also showed that both the magnetization intensity of Myoken-Dake and No-Dake lavas have lower than Fugen-Dake lava. In addition, magnetization lows of 1.0A/m predominate around Inao-Yama (K), a parastic dome on the eastern flank of Fugendake. Nakatsuka (1994) also showed similar results using high-altitude aeromagnetic data.

Ozima *et al.* (1992) found that rocks from different eruptions possessed considerably different magnetization values, because the magnetic properties reflect different oxygen fugacity during the cooling of the rocks. This may be the reason for the variations of magnetization values, even if the surface is covered by a lava.

(3) As shown in Fig.3, magnetization lows locally predominated in this mapped area. The origins of the magnetization lows are suggusted as follows.

(i) Magnetization lows of less than 0.5A/m, which exist around Unzen hot spring (L), Ishiwari-Yama (M), northwestern of Kunimi-Dake (N) and the area surrounding Iwatoko-Yama (O), are associated with the collapsed walls generated by the volcano activity. It is thought that these rock bodies with remanent magnetization were fractured into pieces landslides and then rotated into random directions.

(ii) The magnetism lows around Unzen hot spring (L) are correlated to not only the collapsed walls but also to the hydrothermal alteration zone. Therefore, another possible explnation for the low magnetization is the loss of magnetic minerals in rocks due to hydrothermal activity.

(iii) The lowest values of magnetization <0.0A/m (P), which occur in the valley, correspond to the Kureishibaru pyroclastic flow deposit, suggesting that this feature is the cause of the magnetization low. Magnetization lows of <0.5A/m also predominate around Minami-Senbongi (Q), which is an alluvial fan. A borehole of the Unzen Scientific Drilling Project (USDP) on the northeastern flank of Minami-Senbongi found that the subsurface contains block-and-ash flow deposits and lahar and debris avalanche deposits (Hoshizumi *et al.* 2002). It is thought that these types of rocks of the subsurface around Minami-Senbongi would have low magnetizations, which is consistent with our interpretations.

First, as preliminaly estimation, the averaged magnetization of the survey area was derived to be 3.1A/m in the survey area. Please note that in the surveyed area there is no previous estimation of the apparent magnetic susceptibility of rocks. The average magnetization estimated in previous aeromagnetic surveys is of 2.9 A/m (Nakatsuka, 1994) in a relatively large region of 23 km by 33 km and of 5.1 A/m (Mogi *et al.*, 1995) in a smaller area of 5.5km by 8 km. The value obtained for the small survey area reflects the presence of the highly magnetized Maruyama rocks and the absence of of the low-magnetized Heisei lava. Therefore, in this study, the average value of magnetization is more reliable comparing with the results of previous aeromagnetic analysis. As Unzen volcano is mainly composed of lavas and pyroclastic products of andesite, we believe that this value is correctly estimated.

Our results obtained from the aeromagnetic surveys with spiral trajectories are consistent with past aeromagnetic analyses and showed a good correlation with the surface geology and topography. In addition, this study investigates the spatial magnetization intensity distribution of Unzen Volcano and may offer as well some information on the temporal changes of the volcanic activity.

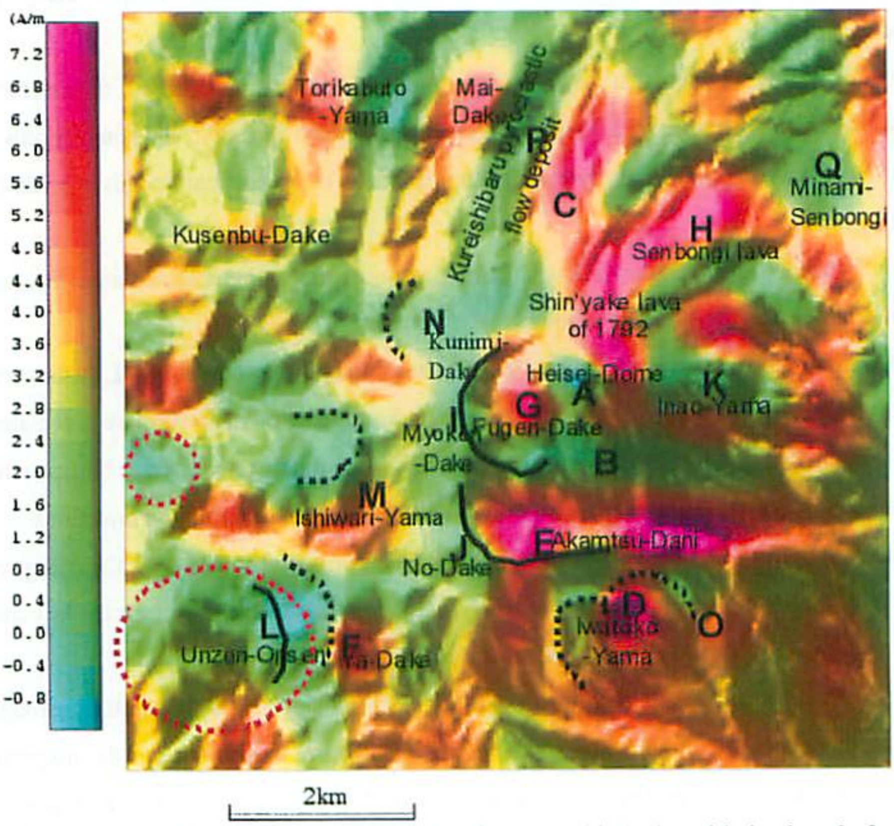

Fig3. Result of the magnetization intensity mapping with a topographic shading and the locations of collapsed walls and the alteration zone after Watanabe and Hoshizumi(1995). Letters (A-Q) correspond to those in table2. Thick solid lines indicate confirmed collapsed walls, while probable or possible ones are shown as broken or dotted lines. In addition, the broken or dotted red lines indicate the alteration zone.

5. Conclusions

We conducted two aeromagnetic surveys of different flight altitudes, over Unzen Volcano using both spiral and constant altitude trajectories. From the total intensity data from the two aeromagnetic surveys, precise magnetic anomaly maps were derived for each observation point by removing the effects of diurnal magnetic variations and the spatial distribution obtained from IGRF 2000.

The statistical average of the terrain magnetization of Unzen volcano was estimated to be 3.1A/m, when the short wavelength anomaly caused by topography relief is eliminated.

The two aeromagnetic anomaly distributions on surfaces of different elevations are upward continued using an equivalent anomaly method. These data were used in a joint inversion to estimate the magnetization intensity map of Unzen volcano.

The resultant magnetization intensity map shows a good correlation with the results of past aeromagnetic analyses and with the surface geology and topography, in general. Lavas of Unzen volcano possess different magnetization values for each eruption event. In addition, magnetization lows correspond to areas such as, hydrothermal alteration zones, suggesting a loss of magnetic minerals due to hot spring activity. Also, the regions of collapsed walls, valley deposits and fan deposits show magnetization lows that are associated with deposits of randomly oriented magnetizations. The Heisei-Shinzan lava, which was formed during the 1990-1995, eruption shows low magnetization intensity values. This lower intensity indicates that the volcanic rocks on Heisei-Shinzan have not yet cooled completely.

Table 1. Specifications and equipment utilized in this aeromagnetic survey.

Survey date	September 18, 2002
Range of survey area	32°43.6'N - 32°48.0'N
	130°14.4'E - 130°20.4'E
Helicopter	a disaster prevention helicopter in Nagasaki Prefecture
Air base	Shimabara heliport
Positioning(sampling interval)	GPS (the helicopter survey:1.0 sec, the ground survey:3.0 sec)
Main magnetometer	GEOMETRICS
type	Optical pumping
Sensor mounting	in the sensor bird
sampling interval	0.5 sec
Sub magnetometer	GEM
type	Overhauser proton
Sensor mounting	over sensor bird
sampling interval	1.0 sec
Reference magnetometor	Proton precession in Mayuyama dam site
sampling interval	3.0 sec

Acknowledgments. We are grateful to N. Oshiman, T. Nakatsuka, S. Okuma, R. Kubota, R. Yoshimura, and K. Yamazaki for useful discussions and helpful criticism. We also would like to express our appreciation to James Mori for his help to improve the quality of this research.

References

Grauch, V. J. S., A new variable-magnetization terrain correction method for aeromagnetic data, *Geophysics.*, **52**, 94-107, 1987.

Hoshizumi, H., K. Uto, A. Matsumoto, S. Xu and K. Oguri, Geology of Unzen volcano and core stratigraphy of the flank drillings, *Unzen Workshop 2002: International workshop on Unzen Scientific Drilling Project (USDP).*, 4-8, 2002

Makino, M., T. Nakatsuka, R. Morijiri, Y. Okubo, S. Okuma, and Y.Honkura, Derivation of three-dimensional distribution of geomagnetic anomalies from magnetic values at various elevations, *Proc. 88th SEGJ Conf., Soc. Explor. Geophys. Japan*, 502-507, 1993 (in Japanese).

Mogi, T., Y. Tanaka, T. Morikawa, K.Kusakabe, M. Tanahashi, T. Nakatsuka, K. Tanaka and H. Utada, Subsurface Structure of Unzen-Fugen and Mayu-yama Volcano Inferred from Airborne Electromagnetic Method and Magnetic Survey, *Kazan.*, **40**, 263-276, 1995 (in Japanese with English abstract).

Nakatsuka, T., Aeromagnetic anomalies over the area of Unzendake volcano, Central Japan, *J. Geomag. Geoelectr.*, **46**, 529-540, 1994.

Ozima, M., T. Hashimoto, and Y. Tanaka, Magnetic properties of some volcanics from Mt. Unzen, *Abstracts 92nd SGEPSS Fall Meeting*, C12-04, 1992.

Watanabe, K. and Hoshizumi, H. GEOLOGICAL MAP OF VOLCANOES 8 (1:25,000). *UNZEN VOLCANO. Geol. Surv. Japan*, 1995

Table 2. Characteristics of the distribution of magnetization intensity on Unzen Volcano. (H) and (L) in remarks denote magnetization highs and lows, respectively. Letters in the first column are correspond to Fig. 3.

SYMBOL (REMARKS)	LOCALITY	MAGNETIZATION INTENSITY(A/m)	GEOLOGIC FEATURES
A(L)	Heisei-Shinzan(Dome)	< 0.5	Heisei Lava of 1991-95
B(L)	EW area south of the Dome	< 0.5	Block-and-ash flow deposits of 1991-95
C(H)	2km nothern of Dome	7.0	Lava flows of Older Unzen Volcano
D(H)	Iwatoko-Yama	6.5	Lava flows of Older Unzen Volcano
E(H)	Akamatsu-Dani	7.5	Lava flows of Older Unzen Volcano
F(H)	Ya-Dake	4.0	Lava flows of Older Unzen Volcano
G(H)	Fugen-Dake	6.5	Fugendake, Kazaana and Shimanomine Lavas
H(H)	2km northeastern of Dome	7.5	Senbongi Lava
I(L)	Myoken-Dake	1.5	Main volcanic edifice (Myokendake Lava)
J(L)	No-Dake	1.5	Nodake lava
K(L)	around Inao-Yama	1.0	Inaoyama Lava
L(L)	around Unzen-Onsen	< 0.5	Hot spring and around collapsed wall
M(L)	around Ishiwari-Yama	< 0.5	around collapsed wall
N(L)	northwestern of Kunimi-Dake	< 0.5	around collapsed wall
O(L)	the area surrounding Iwatoko-Yama	< 0.5	around collapsed wall
P(L)	eastern of Mai-Dake	< 0.5	Kureishibaru pyroclastic flow deposit (valley)
Q(L)	around Minami-Senbongi	<0.5	block-and-ash flow deposit (alluvial fan)