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

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Synopsis

On September 18, 2002, we conducted a high-resolution, low-altitude helicopter-borne aeromagnetic survey over Unzen Volcano. Therefore, we conducted a magnetization intensity mapping on the volcano, on the assumption that the magnetic anomalies are caused by the terrain magnetized in the same direction as the present Earth's magnetic field and the magnetization intensity varies only laterally. This map shows good agreement with the geologic features, especially the hydrothermal alteration zone and the collapsed pyroclastic deposits. In addition, even in the area covered by lavas, the magnetization intensities show various values corresponding to each eruption event. Local magnetization lows on Heisei-Shinzan suggest that the Heisei lava produced by the 1991-1995 eruption has not yet been cooled enough.

Keywords: Unzen volcano, helicopter-borne magnetic surveys, aeromagnetic anomalies, magnetization intensity map

1. Introduction

The Unzen volcano (Fig.1) is located on the Shimabara Peninsula, the western extremity of a large graben across Central Kyushu, Japan. Almost all lava domes and other volcanoes are distributed among the "Unzen Graven" caused by E-W trending faults, such as the Chijiwa, Kanahama and Futsu faults.

Unzen volcano began phreatic eruptions in November, 1990 at the summit craters after a quiescence of 198 years. After intensive ash ejections in February 1991, a lava dome appeared near the eastern area of the previous peak of Mt. Fugen in May, 1991. The lava dome, named Heisei-Shinzan, gradually grew on the eastern flank of Mt. Fugen and yielded frequent pyroclastic flows until the eruptive activity ended in 1995.

Past magnetic analyses (Nakatsuka, 1994; Honkura et al., 1995; Mogi et al., 1995) have been conducted using aeromagnetic survey data over Unzen Volcano. Nakatsuka (1994) found a characteristic graben structure and an old volcanic unit unknown around Sarubayama from a high-altitude aeromagnetic survey at 7,500 feet. Although the results provide information on a structure of wider scale in perspective, they didn't obtain the more detailed information in the surface. In the study of Honkura et al. (1995), although they attempted a blimp-borne magnetic survey, positioning data were not very accurate and flight passes were not sufficient to cover all the mountains of Unzen Volcano. In additton, although Mogi et al. (1995) carried out a low-altitude aeromagnetic survey over the target area including Mayuyama volcano, they didn't contain in and around Heisei-Shinzan.

In this study, we conducted two low-altitude aeromagnetic surveys using spiral trajectories with good positioning accuracy over Unzen volcano containing Heisei-Shinzan. For detailed analyses and interpretations of the magnetic anomalies, we carried out a magnetization intensity mapping on the volcano using the aeromagnetic anomalies at two surface elevations considering a large number of data. In this paper, we discuss the relation between our results, geology and topography of the volcano.

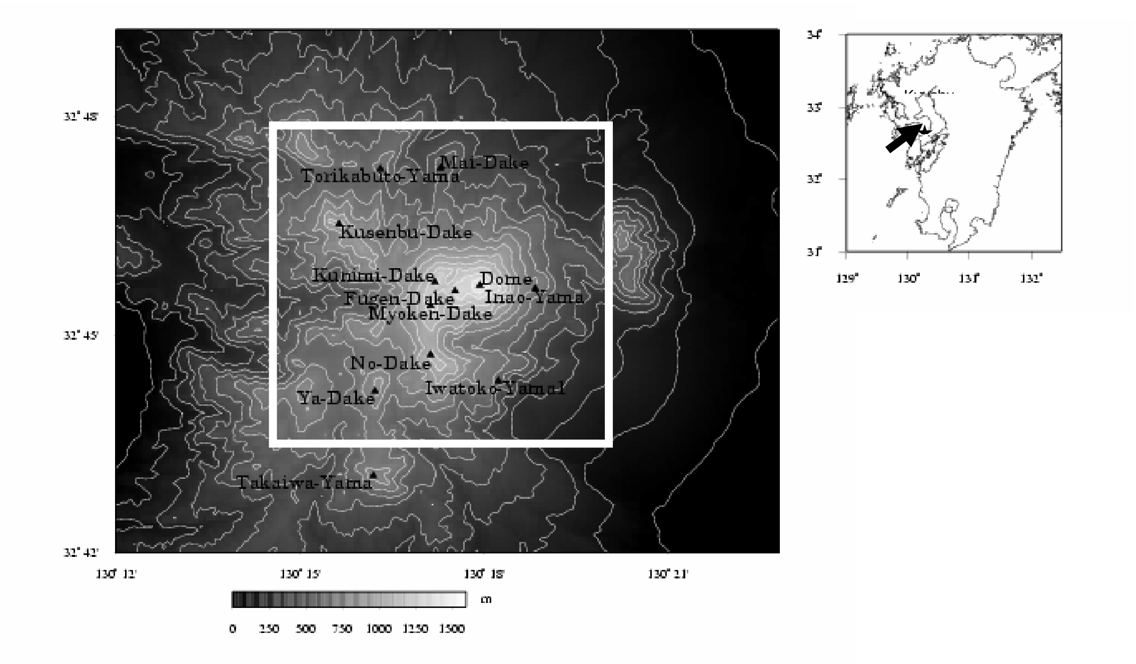

Fig.1. Location and topography of Unzen volcano, Kyushu, Japan. Contour interval is 100m. The box shows the survey area in this study.

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 a 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 (*Flight_H*) above the ground, the other is at 180m (*Flight_L*). The standard deviations of altitude are 64.6m and 57.7m, respectively. Fig.2 show 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. 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.

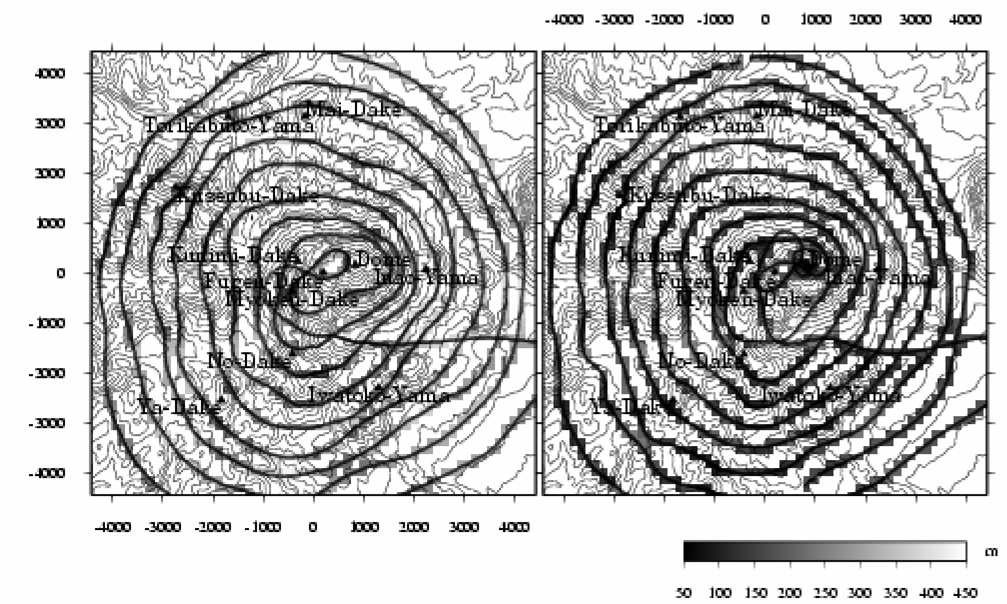

Fig.2. The spiral lines indicate trackline paths of the aeromagnetic surveys and the gray contours shows the observed altitude above the ground for *Flight_H* and *Flight_L*, respectively. Topographic contour interval is 50m.

3. Method

3.1 Estimation of Terrain Magnetization

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. To perform this estimation, the terrain altitude data in a 50m-grid were prepared for the area contained survey area of 30.0km by 30.0km. The terrain effect was synthesized by an assembly of small prismatic bodies. The top depths coincide with the topographic surface and the bottom depths are assumed to be 500m below sea level.

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 described in the next subsection.

3.2 Derivation of 3-D Distribution of Geomagnetic Anomalies using the Equivalent Anomaly Method

We consider derivation of a three-dimensional distribution, which has regular grid intervals. So, using a procedure developed by Makino et al. (1993), we reduced terrain corrected anomalies on an irregular surface onto an equivalent anomaly surface, and applied it to get the upward continued.

We obtained upward continued anomalies on a surface parallel to the topographic relief of this survey area, because the flight altitude followed the topography. This method extracts harmonic components and provides upward continuied values, along with reducing the noise caused by the observations. Fig.3 show the results of upward continued anomalies and are used as input data in the magnetization intensity mapping method discussed in the next section. In this study, the equivalent anomalies are the results of the iterative solution in the conjugate gradient (CG) method by the iteration terminated until 20 trials. Here, the surfaces of equivalent anomalies were regularly distributed 600m under observed anomaly surfaces which have wider area 1.8km beyond the survey area in order to avoid edge effect, respectively. 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.

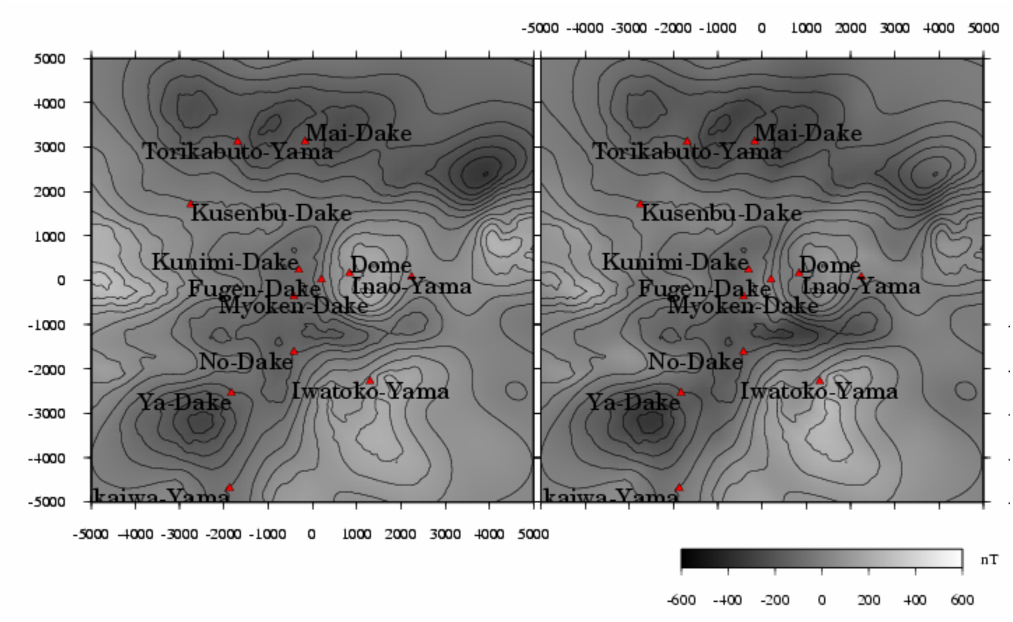

Fig.3. Upward continued magnetic anomalies to the surface, which is 500m higher than the average altitude of the actual observations for both *Flight_H* and *Flight_L*. The contour intervals in each case are of 50nT.

3.3 Magnetization Intensity Mapping

We applied the magnetization intensity mapping method to the anomalies of Fig.3 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.3 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.4. 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.

4. Results and Discussion

We discuss some characteristics of the distribution of the magnetization intensity, as shown in Fig.4, 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.

(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.4, 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 explanation 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 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.

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 addi tion, 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 Hei sei-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.

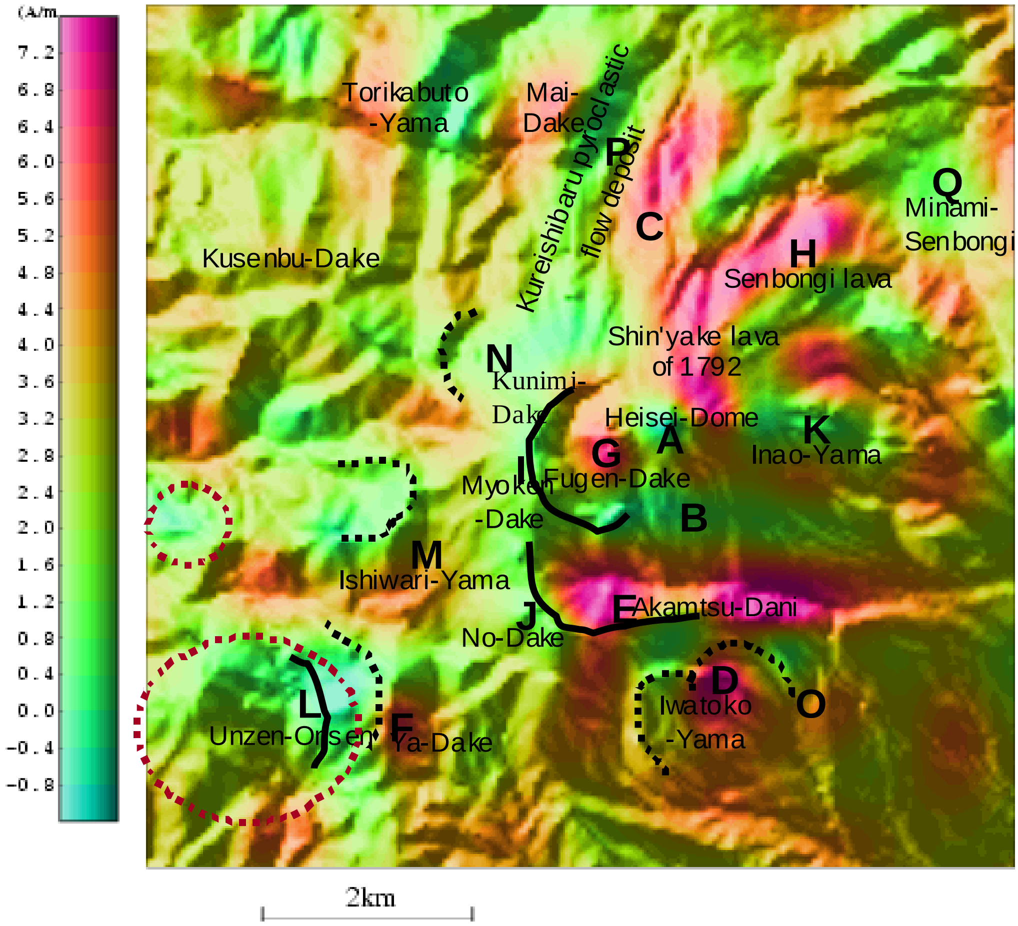

Fig.4. Result of the magnetization intensity mapping with a topographic shading. The magnetic anomalies of Fig.3 were the input data for the inversion process. Assumed sources were distributed in wider area of 12km by 12km, but the results are shown only for 8.4km by 8.4km, within the range of the input data. Block solid lines indicate confirmed collapsed walls, and probable or possible ones are shown as broken lines after Watanabe and Hoshizumi (1995), while the broken red lines indicate the alteration zone.

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雲仙火山における低高度な高密度空中磁気探査

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要　旨

雲仙科学掘削の一観測項目として、長崎県防災ヘリの協力をえて、2002 年 9 月 18 日に雲仙岳を中心とする低高度な高密度空中磁気探査を実施した。

近年の噴火は、1990 年 11 月 17 日に地獄跡火口と九十九島火口における水蒸気噴火に始まり、翌年の 2 月の屏風岩火口からの火山灰噴出の後、5 月に地獄跡火口に溶岩ドームが出現した。噴出した溶岩の多くは、ローブ状に東部斜面に張り付くとともに内性的成長を続けドーム状の平成新山を形成した。山頂近くで磁場の連続および繰り返し観測がなされているが、地上観測では測点が限られ、面的に磁化構造を把握しきれない。また雲仙火山地域における過去の空中磁気探査では、Nakatsuka(1994)、Mogi et al(1995)、 Honkura et al(1995)などが挙げられるが、飛行高度、Target 領域および位置精度の問題が存在し、雲仙火山とその周辺における詳細な磁化構造は把握しきれていないのが現状である。また、空中磁気探査界において飛行航跡をスパイラル飛行としたのは、世界初であることも特記しておきたい。

本研究の目的は、1.雲仙火山とその周辺の詳細な磁気異常分布から地下の磁化構造を推定し、火山活動と関連する地質構造や熱構造等を明らかにすること、2. 雲仙の火山活動に関連する、雲仙地溝の詳細な 2 次元磁化構造を明らかにすることである。

調査飛行は、2 高度面（対地高度約 320m および 180m）同じ領域で行われ、両高度面ともに普賢岳を中心とする概ね 10km 四方の範囲のスパイラル測線である。

本調査では急峻な地形に沿っての飛行の為に、普賢岳平成新山地域では 1600-1700m と高く、飛行高度に約 1200m 程度の差があると同時に、スパイラル測線のため、データの密度に偏りもある。そこで、観測高度を滑らかな曲面にグリッド化させ、且つ磁気異常のノイズを取り、長周期分の波長を抽出する目的で、観測高度下に地形補正済み磁気異常を説明する equivalent anomaly(Makino et al, 1993)を inversion により求め、観測高度面に並行する鉛直 500m 上の基準面に引き直した。この磁気異常値を入力値として、2 高度面を同時に、ジョイント・インバージョンを行った。なおデータの個数は 2 高度分の 6498 個、未知数は入力データ範囲の 1.8km を覆う 6400 個とし、データと未知数のグリッド間隔は各々150m で、20 回の反復計算より求めた。

今回得られた磁化強度マッピングから、以下の点を明らかにした。

1. 雲仙火山における溶岩の磁化強度は各々の噴火に対し、値がかなり異なる.
2. 平成新山は低磁化強度を示し、溶岩が完全に冷却されていないことが示唆される。
3. 崩壊壁や温泉と今研究で得られた低磁化強度域は一般的に良く一致している。

キーワード：雲仙火山、　空中磁気探査、磁気異常、　磁化強度マッピング