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Magnetization Structure of Unzen graben Determined from Aeromagnetic Data

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Synopsis

Aeromagnetic analyses have been conducted in and around Unzen Volcano, Kyushu, Japan, in order to reveal the subsurface structure of the Unzen graben. Finally, also from a viewpoint of magnetization structure as pointed out by the result of other geophysical data, it turns out that the Unzen graben has the feature of half-graben, which northern fault fallen in the western Unzen region and southern fault fallen in the eastern Unzen region, moreover, it clarified that magnetization lows (expand from east to west) corresponding to the hydrothermal alteration exists in the center part in the graben.

Keywords: Aeromagnetic analyses, Unzen graben, magnetization structure

1. Introduction

Unzen volcano (Fig. 1) has been formed in the Unzen graben in a N-S extensional tectonic stress field. This volcano is cut by EW-trending normal faults, such as Chijiwa-, Kanahama-, Futsu- and Fukae-faults. Although these E-W trending normal faults run in the middle of the Shimabara Peninsula, the northern and southern boundaries of the graben are not clear because volcanic rocks have almost entirely filled the depression.

In this study, we aim to clarify a magnetic structure of the Unzen graben which progressed with volcanic activity and has been related closely, and to discuss the tectonic and geothermal subsurface structure based on these results. First, we reanalyzed the aeromagnetic data of August, 1991 (Nakatsuka, 1994) in order to clarify the regional spatial distribution of geology in the central part of the Shimabara peninsula. Next, we give new knowledge for main faults forming the Unzen graben by using low-altitude aeromagnetic data of 2002. These data allow us to identify the extent of individual geologic units, dislocations of faults, and the distribution of hydrothermally altered areas. Finally, we reveal 2.5-dimentional models for 3-dimensional interpretation and and discuss about these results based on other geophysical and drilling data accumulated so far

2. Aeromagnetic Data

In Unzen Volcano, among several data sources of aeromagnetic surveys conducted at different epochs with varying survey specifications (NEDO, 1988; Nakatsuka, 1994; Mogi et al., 1995; Okubo et al., in press), the following two data are useful to discuss the tectonic and geothermal subsurface structure of the Unzen graben.

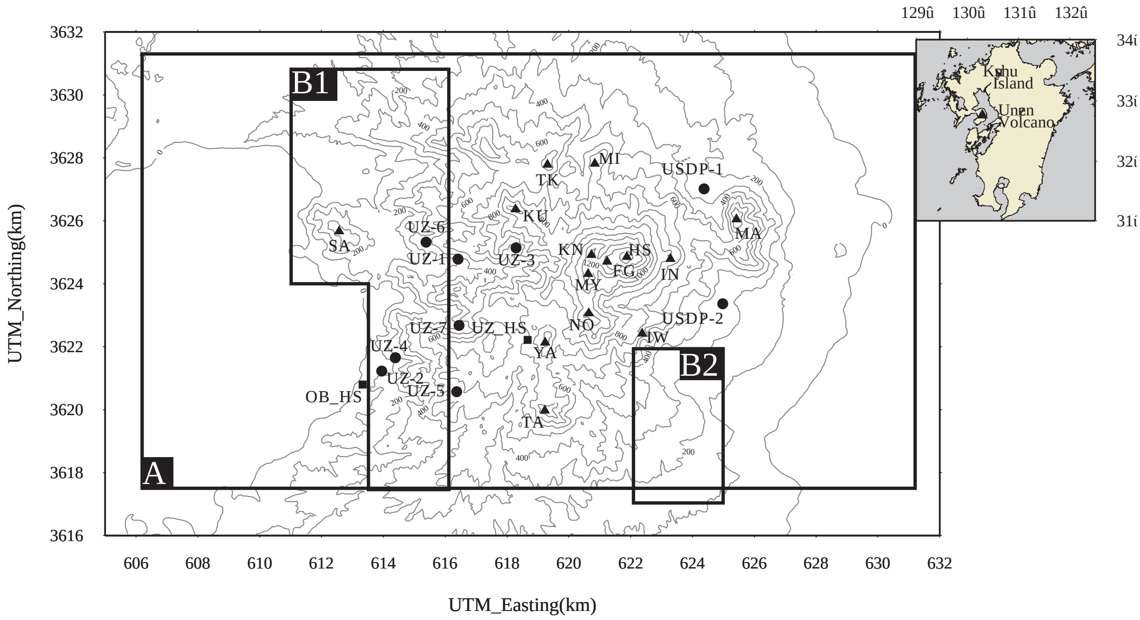

Fig.1. Topographic map of the central part of the Shimabara Peninsula. Contour interval is 100m. Box A shows the high-altitude aeromagnetic data area in 1991, and boxes B1 and B2 show the low-altitude aeromagnetic data area in 2002. Solid circles of UZ-1 to -7, and USDP-1 and -2 show the locations of drilling sites and numerals show the altitude (above sea level) of the top surface of basement rocks of Unzen volcano. Thick lines indicate normal faults after Hoshizumi et al. (2002). MA=Mayu-Yama; IN=Inao-Yama; IW=Iwatoko-Yama; FG=Fugendake; HS=Heisei-Shinzan; MI=Maidake; TK=Torikabuto-Yama; KN=Kunimidake; KU=Kusenbudake; MY=Myokendake; NO=Nodake; YA=Yadake; TA=Takaiwa-Yama; SA=Saruba-Yama; UZ-HS=Unzen hot spring; OB-HS=Obama hot spring.

magnetization intensity mapping by combining with drilling data of UZ-1 to -6 and USDP-1 and -2.

2.1 High-altitude data in 1991

An aeromagnetic survey covering the central part of the Shimabara peninsula was flown in August, 1991, after the commencement of recent eruption (Nakatsuka, 1994). Although it was before the formation of Heisei-Dome, the data from this survey is still useful, because it doesn't discuss on Heisei-Dome here. A total of 26 traverse lines in the E-W direction and 5 tie lines in the N-S directions were flown at an altitude of 7500 ft (2300 m) above sea level. Average line spacing of traverse lines is about 500m uncovering above the summit lava dome. Finally, Nakatsuka (1994) presented three-dimensional rough model of the graben by the analysis of the terrain corrected anomaly. However, further analysis in consideration of geological data was left.

Therefore, in order to discuss more detailed the tectonic and geothermal subsurface structure in the Unzen graben, we re-analyzed the same data, where the magnetic modeling are performed based on the results of

2.2 Low-altitude data in 2002

As low-altitude data, a helicopter-borne aeromagnetic survey was carried out on September 18, 2002. This survey was flown across the Futsu and the Fukae faults and across the Chijiwa and the Kanahama faults at a low altitude along the rugged topographic relief. The average flight altitude was about 500m above sea level. After the correction for terrain effect (cf. Bhattacharyya, 1964; Nakatsuka, 1981), we reproduced magnetic anomaly maps of boxes B1 and B2 at the reduction altitude of 850m above sea level using a procedure developed by Makino et al.(1993).

3. Data Analysis

3.1 Magnetization Intensity Mapping

In order to obtain information on the regional subsurface structure using the terrain corrected data, such as lava flows, pyroclastic flows, fructured and hydrothermally altered areas, we applied the magnetization intensity mapping method (e.g. Okuma, 1994; Nakatsuka, 1995) by using data of Nakatsuka (1994). See Fig. 2.

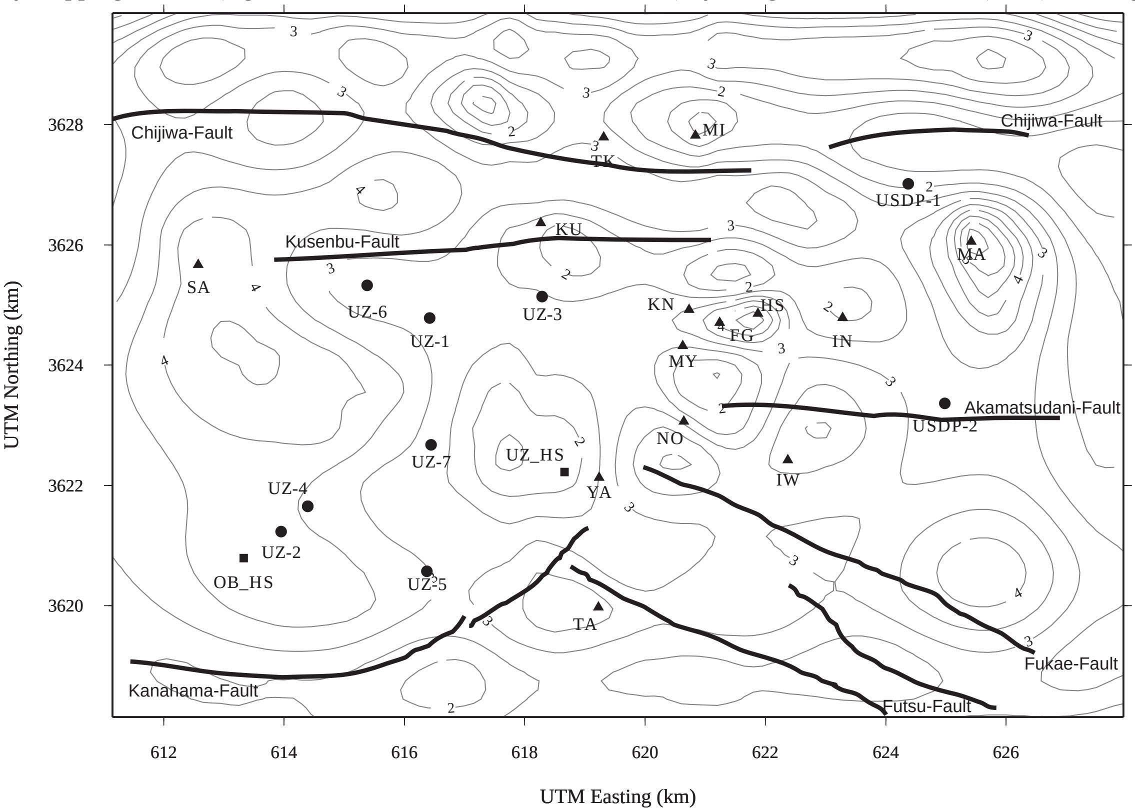

Fig.2. Result of magnetization intensity mapping for the box A. The terrain corrected anomalies are the input data for the inversion process.

3.1.1 Results

Characteristics of the obtained regional magnetization intensity distribution in the central part of the Shimabara peninsula (Fig. 2) are summarized as follows.

For the western Unzen region, generally, magnetization highs (about 4.5 A/m) predominate on the Older Unzen volcano, for example, it is distributed around Saruba-Yama. However, magnetization lows (about 1.0 A/m) distributes around Unzen hot spring, and expands in East-West in south side of the Kusenbu fault. These areas correspond to the hydrothermal altered areas causing a large loss of magnetic minerals in the volcanic rocks.

On the other hand, for the eastern Unzen region, magnetization highs (about 6 A/m) predominate on Mayu-Yama volcano, while magnetization lows (about 1.0 A/m) predominate on the circumference of Mayu-Yama. It is supposed that the Mayu-Yama lava has the extremely high magnetization on Unzen Volcano. The fan deposit located between Mayu-Yama volcano and Fukae fault shows magnetization highs, and there is a clear magnetization intensity associated with the Fukae fault. This suggests that magnetic fan deposits are thickly accumulated inside the graben.

Magnetization lows predominate outside of the main faults forming the Unzen graben (i.e., to the North of Chijiwa fault, and to the South of Kanahama, Fukae, and Futsu faults). However, the magnetization highs are distributed with an E-W trend north of the Chijiwa fault. It is considered to be the effect of lavas on the Older Unzen volcano, which was supplied out of the graben (see Fig. 2), because the supply rate was higher than the subsidence. Moreover, it is suggested that the magnetization of the Pre-Unzen must be weak (about 1.0 A/m) because the Pre-Unzen volcanics distribute near the surface south of the Kanahama fault (see Fig. 2). Generally, the above results have a good correlation with the measurements of NRM intensity (Tanaka *et al.*, 2004).

3.2 Forward Modeling for Magnetic structure

We used 2.5 dimensional, foward-and-inverse magnetic profile modeling program (Webring, 1985). In order to simplify the modeling process, these terrain corrected anomalies were derived terrain reduced-to-pole aeromagnetic anomalies using the method by Baranov and Naudy (1964) (see Fig. 3). The total magnetization used in this forward calculation is a vector sum of the induced and remanent magnetization. A 2.5D foward-and-inverse modeling along profiles crossing the main anomalies showed was performed. All the selected profiles produced by slicing this terrain reduced-to-the-pole magnetic anomaly grids are assumed that both the magnetic field and the magnetization vector are vertical.

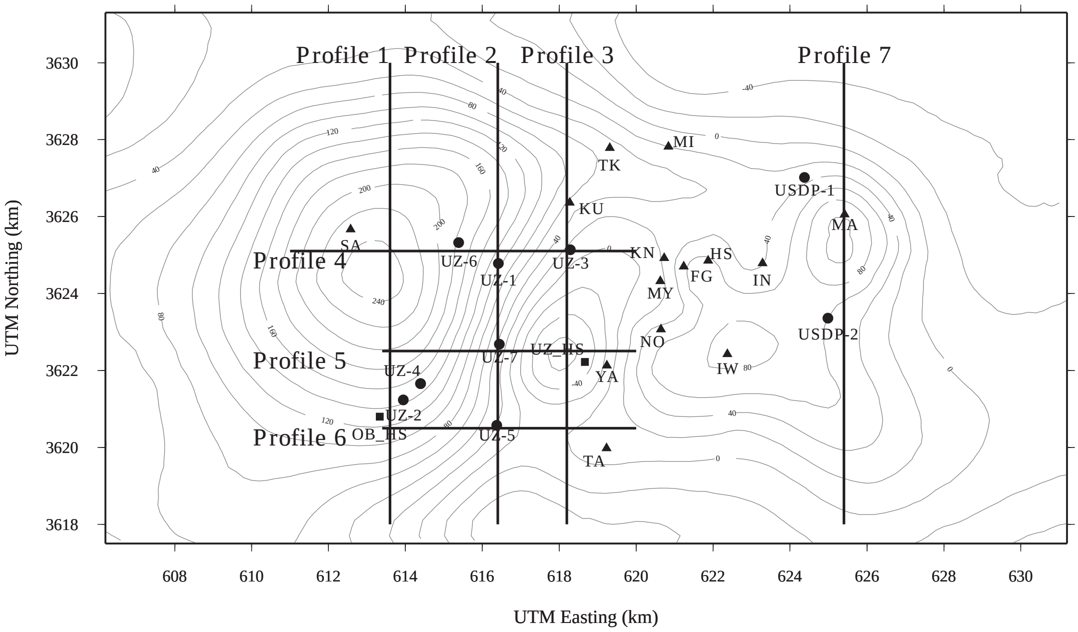

Fig.3. Terrain corrected reduced-to-pole magnetic anomaly map of box A, and the locations of profiles of forward modeling. Contour interval is 20 nT.

We adopted the average magnetization intensities of 4.5 A/m for the Older Unzen volcano lava, and 1 A/m for the layers of the Pre-Unzen volcanics or the hydrothermally altered area, based on the result of the magnetization intensity mapping (Fig. 2). In addition, the magnetization intensity of the Mayu-Yama lava was assumed to 6 A/m, while the Younger Unzen, consisting mainly of collapse or lahar products of No-Dake, Myoken-Dake and Fugen-Dake, was assumed to 1 A/m, from the result of magnetization intensity mapping (Fig. 2). These results show in Fig. 4.

3.2.1 Results

The N-S sections along profiles 1-3 in the western Unzen region are shown in Fig. 4(a)-(c). In Profile 1, the layer of 4.5 A/m is deposited inside the graben thickly bordered at the Chijiwa fault and the Kanahama fault. However, in profile 2, the layer of 4.5 A/m is thinner around Kanahama fault while it is thick around the Chijiwa fault. In profile 3, there is same tendency as profille 2, although the layer of 1.0 A/m reaches the surface around Unzen hot spring.

The E-W sections along profiles 4-6 in the western Unzen region are shown in Fig. 4(d)-(f). In Profile 4, the layer of 4.5 A/m becomes thinner to the east, from Kami-Dake (UZ-1) to Shimo-Dake (UZ-3), and further east from UZ-6. In profile 5, although the layer of 4.5 A/m is thick in the western part, the layer of 1.0 A/m reaches the surface around Unzen hot spring as well as in profile 3. In profile 6, the thickness variation of the layer of 4.5 A/m becomes a little calm, still having the same tendency in profile 5.

In the N-S section along profile 7 in the eastern Unzen region (Fig. 4(g)), forward modeling was performed dividing magnetization intensity of Mayu-Yama lava in 6 A/m. It was shown that magnetization low becomes deep in the area placed between Chijiwa fault and Futsu and Fukae fault, magnetization high occupies the inside, and the south is deeper. In addition, magnetization high area exists in Mayu-Yama.

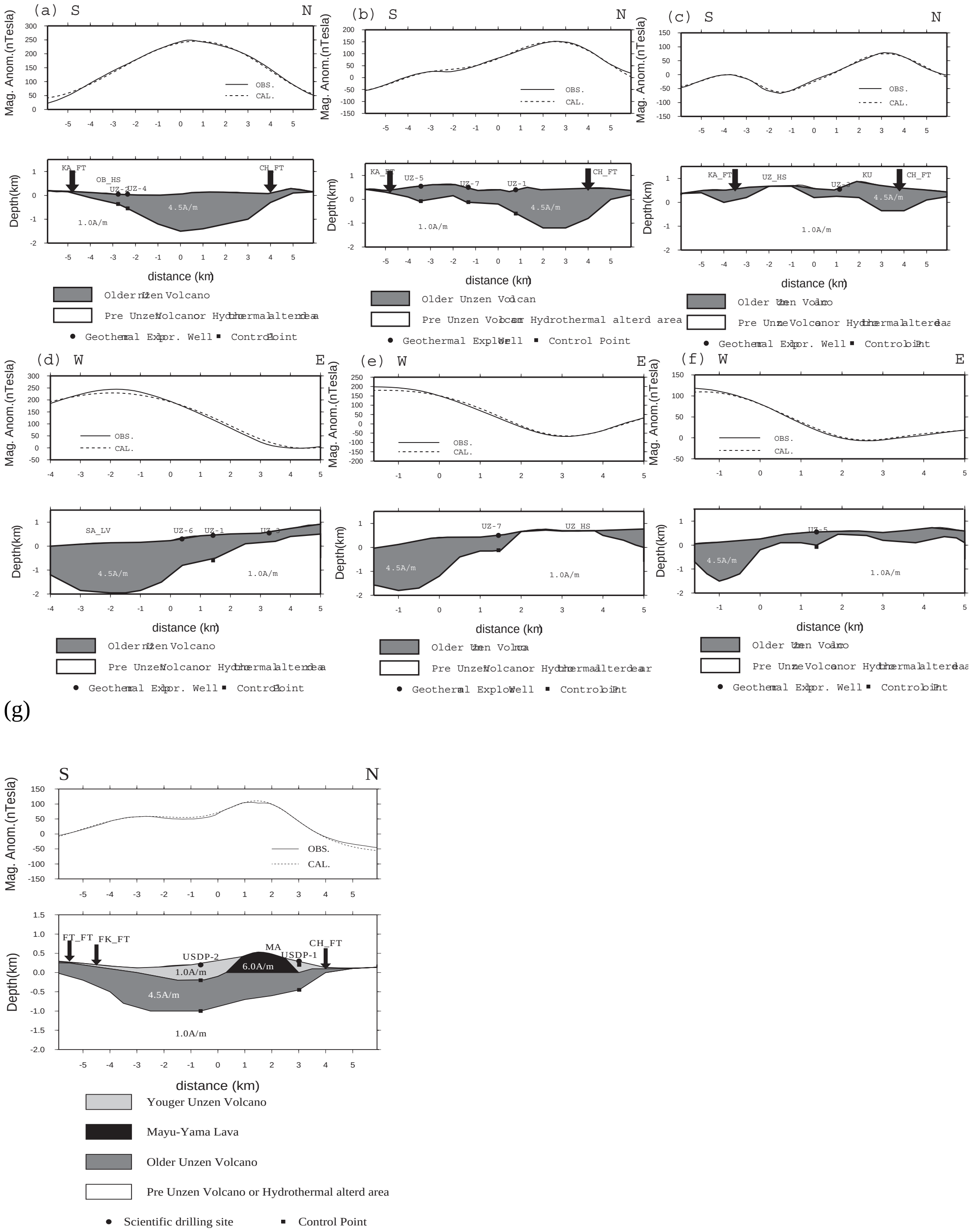

Fig.4 Results of the magnetic modeling along N-S profiles [(a) profile 1, (b) profile 2, (c) profile 3 and (g) profile 7] and E-W profiles [(d) profile 4, (e) profile 5 and (f) profile 6] shown in Fig. 3. Squares indicate the control points used for modeling after NEDO (1988).

3.3 Horizontal Gradients and Boundary Analysis

To lack the resolution, the high altitude data was not able to clarify the boundary of the main fault so much. Therefore, in this section, we performed horizontal gradients and boundary analysis using low-altitude aeromagnetic data, in order to understand more detailed and localized feature of the main faults qualitatively. In general, the lineaments delineated by the pseudo-gravity gradients represent deeper or more regional boundaries than those by the reduced-to-pole gradients (c.f. Blakely, 1995; Finn and Morgan, 2002).

3.3.1 Results

For box B1 in Fig. 5, there exists a pseudo-gravity anomalies along the Chijiwa fault, while no sign exists along the Kanahama-fault on neither the reduced-to-pole or the pseudo-gravity. As the horizontal gradient of the pseudo-gravity anomaly is considered to reflect the influence of deeper boundaries than the reduced-to-pole anomaly, it is thought that the graben structure has subsided rapidly in the deeper locations along the Chijiwa fault. On the other hand, along the Kanahama fault, no clear boundary exists, and the subsidence of the Kanahama fault is considered to be small compared with the Chijiwa fault. Although several peaks in the horizontal gradient magnitudes also appeared around the foot of Saruba-Yama and to the east (Figs. 4(a) and (b)), they are considered to be zones of hydrothermally altered or fructured rocks.

For box B2 in Fig. 6, there is a magnetic boundary along the Fukae fault, while no magnetic feature is associated with the Futsu fault. This result is consistent with the regional magnetization distribution (Fig. 2). It is thought that the Fukae fault has dislocated much more than the Futsu fault.

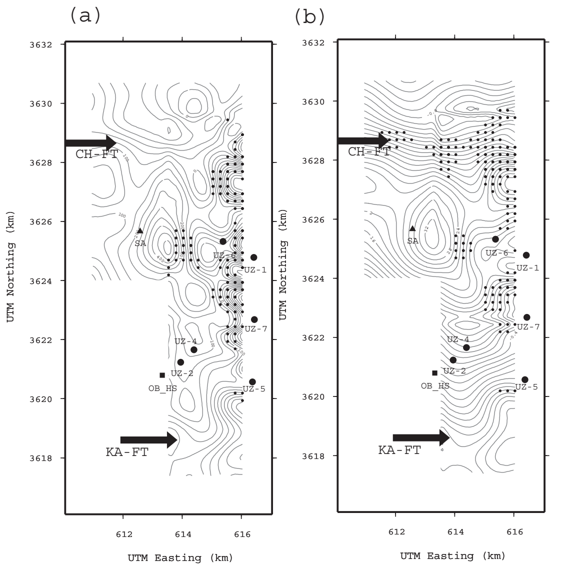

Fig. 5. Results of boundary analysis for the box B1 applied to (a) reduced-to-pole, and (b) pseudo-gravity anomalies of terrain corrected magnetic anomalies. Small dots indicate the peak areas in the horizontal gradient magnitudes (a) > 500 nT/km, and (b) > 1.6 Pseudo mGal/km. Line contours indicate (a) reduced-to-pole anomalies with the interval of 50 nT, and (b) pseudo-gravity anomalies with the interval of 0.2 Pseudo mGal/km, respectively. CH-FT=Chijiwa Fault; KA-FT=Kanahama Fault.

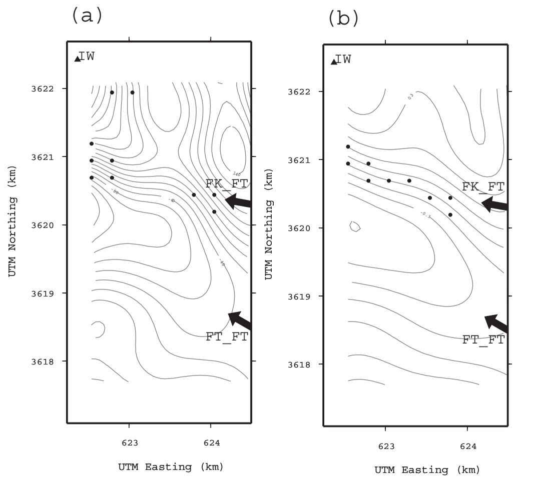

Fig.6. Results of boundary analysis for the box B2 applied to (a) reduced-to-pole, and (b) pseudo-gravity anomalies of terrain corrected magnetic anomalies. Small dots indicate the peak areas in the horizontal gradient magnitudes (a) > 250 nT/km, and (b) > 0.7 Pseudo mGal/km. Line contours indicate (a) reduced-to-pole anomalies with the interval of 20 nT, and (b) pseudo-gravity anomalies with the interval of 0.1 Pseudo mGal/km, respectively. FT-FT=Futsu Fault; FK-FT=Fukae Fault.

4. Summary

4.1 The western Unzen region

Chijiwa and Kanahama faults are known to be the basic frame of the graben in the western Unzen region. From our result of Figs. 2 and 4, it is suggested that lava and the pyroclastic flow of the Older Unzen are deposited thickly with the subsidence of the basement near the Chijiwa fault, while the subsidence of the basement is not clear at the Kanahama fault. The result indicates that the northern and southern faults forming the Unzen graben have different feature, and our result suggests that the subsurface structure in the western Unzen region has a feature of half-graben fallen at the northern fault. Also from the result of MT survey of Utada et al. (1994) and Kagiyama et al. (1992), it is known that the thick layer of high resistivity exists near the Chijiwa fault, while the layer of low resistivity exists under the surface near the Kanahama fault. Therefore, it is also consistent with the result of MT survey.

On the other hand, magnetization lows (about 1 A/m) are distributed around Unzen hot spring and Shimo-Dake (UZ-3). It is difficult to distinguish whether they are the formation of the Older Unzen or the Pre Unzen (basement) from aeromagnetic data only. In particular, our magnetic model demonstrated that the layer of low magnetization (1A/m) extends near surface beneath Shimo-Dake and Unzen hot spring (Fig. 4). According to drilling data (NEDO, 1988) at UZ-3 and other sites, the layer corresponds generally to the hydrothermal alteration or fractured rocks. Kagiyama et al. (1992) also showed that the layer of low resistivity becomes extremely shallow around Unzen hot spring to reach surface at Unzen hot spring. Therefore, it is thought that the rises of the low magnetization layer correspond to the fractured or hydrothermally altered zones caused by the upflow of geothermal convections. Thus, the layer of low magnetization are dominated at Unzen hot spring and at the area from Shimo-Dake to Kamidake reflecting hydrothermal alteration (Fig. 2 and Figs. 4(c) and (e)). However, no magnetization lows are found at Obama hot spring (Fig. 2 and Figs. 4(a) and (f)). It is expected that the scale of the geothermal convection system at the Obama hot spring is much smaller than the one of Unzen hot spring.

4.2 The eastern Unzen region

In the volcanic fans extending southwards, it turns out that the basement was much depressed in the stage of Older Unzen and a thick distribution of the Older Unzen products inside the graben (Fig. 4) exists beneath the younger deposits. In particular, it is shown in our magnetic analysis that the basement subsidence at Fukae fault is remarkable (see Fig. 6). It seems that the axis of the Unzen graben moves south toward east in the Shimabara peninsula (Fig. 4). Thus, the magnetic structure in the western Unzen region has the feature of half-graben fallen at southern fault. The same tendency has been shown also in the geologic cross-section by Hoshizumi et al. (2003) and in the 2D analysis of gravity basement structure (Inoue and Takemura, 2002).

The magnetization intensity of Mayu-Yama lava is much higher than other lavas in Unzen Volcano, which is consistent with the result of analysis from another aeromagnetic data by Mogi et al., (1995). As an evidence from the paleomagnetic study of Unzen (Tanaka et al., 2004), Mayu-Yama lava shows the NRM intensity higher by one order of magnitude than the average of those in the central Shimabara peninsula.

On the other hand, magnetization lows are dominant along Chijiwa fault and on the circumference of Mayu-Yama (Fig. 2). There are two possibilities of causing these magnetization lows. First, they may reflect the distribution of fan deposits of the Younger Unzen in the shallow parts. These rock bodies, even though having remanent magnetization, were fractured into pieces and rotated into random directions. Another possibility is that high-temperature geothermal fluids may cause the hydrothermal alterations of volcanic rocks. Actually, high HCO_3 concentrations are observed around Mayu-Yama and Shimabara and they are believed to come from the addition of CO_2 gases of deep origin ascending along the faults such as the Chijiwa and the Akamatshu-Dani faults (Kazahaya, 2002).

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空中磁気データから推定される雲仙地溝の磁化構造

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要　旨

空中磁気データから雲仙火山の広域的な磁化構造を推定した。雲仙火山地域の過去の空中磁気研究のうち、Nakatsuka(1994)だけが、深さ方向に対する磁化構造解析が行われている。Nakatsuka(1994)では、地殻一様磁化と仮定した底部深度解析により雲仙地溝の磁化構造が決められていたが、地殻一様磁化では、表現しきれない問題が残された。そこで本研究では、Nakatsuka(1994)の1991年に収得された島原半島中部を覆う高高度(海抜高度2300m)な空中磁気データを再度利用して、掘削データから得られた深度方向の情報を取り入れ、かつ磁化強度マッピングにより求められた磁化強度値を採用して、2次元フォワードモデリングから雲仙地溝の磁化構造を推定した。また高高度なデータからは断層のバウンダリを明瞭に示せなかったことから、2002年の低高度なデータを用いて、磁気的構造境界の検出をすることで、断層の落ち込みに対する定性的な議論を行った。これらの結果、磁化構造の観点からも、雲仙地溝の構造は、重力、地質断面およびMT探査の結果から指摘されているように、雲仙西部地域では北落ちのhalf-graben、また、雲仙東部地域では南落ちのhalf-grabenとなることを示した。

キーワード： 空中磁気解析、雲仙地溝、磁化構造