Rockmagnetic study on the debris avalanche deposits of Bandai Volcano

—Debris at 1888 eruption and Okinajima debris—

Hideo SAKAI*a) and Takashi INOKUCHIb)

Abstract

Rockmagnetic studies were conducted on three boring cores drilled at Bandai Volcano of Fukushima Prefecture. The cores include the debris avalanche deposit of 1888 collapse. Debris avalanche deposits in BD 1 and BD 2 cores, with the thickness of 20m and 80m respectively, show a stable remanent magnetization with fairly constant inclination. It suggests that the 1888 debris avalanche deposit was transported without significant deformation, i.e., slid a distance of 1 to 2 km as a block to rest on the area that is BD1 and BD2 at present. In the BD 3 core at the center of collapse area, the magnetizations of the samples show appreciable deflected and scattered directions from the geomagnetic inclination, suggesting that both the debris and the underlying volcanic sequence have been severely fractured.

Rockmagnetism was also studied on the hummocky hill of Okinajima debris avalanche, 5 km from the crater. Eight samples collected from the outcrop (20m high and 80m wide) showed the concentrated direction of remanent magnetization. It indicates that the hummocky hill of the Okinajima debris avalanche (collapse at 80-90ka; Suzuki, 1987) was transported 5 km as a sliding block. Thus, the rockmagnetic method is proved to be useful in the study of transportation and depositional process of mega-block debris avalanches as a huge landslide event.

Key words: remanent magnetization, anisotropy of magnetic susceptibility, Bandai Volcano, debris avalanche deposit, hummocky hill

1. Introduction

In the volcanic area, when gigantic avalanches occur, there is a possibility that the debris is transported as a megablock like a landslide (Moriya, 1978), however it is not easy to find the evidence. This paper attempts to apply the rockmagnetic method to examine this phenomena.

In this paper, we will show the results of rockmagnetic studies on the debris avalanches of Bandai Volcano to investigate their transportation and deposition process through the remanent magnetization and magnetic susceptibility. As for samples, three boring cores are used. These cores were drilled at the northern wall by the National Research Center for Earth Science and Disaster Prevention from 1991 to 1993. The cores include the debris avalanche of 1888 collapse. In addition, Okinajima debris avalanche debris deposit in the south of Mt. Bandai was also used in the rockmagnetic study.

Bandai Volcano (elevation of 1818.6m) is located in the middle of Fukushima Prefecture. It is comprised of Upper Tertiary rocks as the basement complex and consists of Old and New Bandai Volcanoes, even older Pre-Bandai Volcano, and thick tephra deposits along the foothills (Mimura and Nakamura, 1995). Pre-Bandai Volcano is exposed at the lower west wall of the collapsed caldera of 1888. Old Bandai consists of Kushigamine and Akahaniyama volcanic cones, and New Bandai comprises of Ohbandai (erupted in the collapsed area of Old Bandai) and Kobandai. Old Bandai and New Bandai caused the several large scale collapses.

Okinajima debris avalanche, a rockslide avalanche which occurred on Old Bandai Volcano is the largest at Bandai Volcano and accumulated along the south-west foothills. The date of collapse is estimated to be 80-90 kyrs B.P. (Suzuki, 1987).

In the 1888 eruption, due to mountain collapse, a debris flow of 1.5km³ in volume was distributed in an area of 34km² (Nakamura, 1978). Collapsed materials (debris avalanche) descended down from the northern flank, and buried villages and drainages, resulting in the formation of 3 dammed lakes (Lake Hibara, Lake Onogawa, Lake Akimoto) and many small ones. A lot of damage was done, i.e., many houses destroyed, 477 people killed or lost. Sekiya and Kikuchi (1888) looked at the collapse and reported that the rock mass moved downwards (as the water flow). In the slope of the collapsed area, such unique geography as avalanche valleys, hummocky hills were formed.

The geology and characteristics of these avalanches are described in detail by Nakamura (1978), Mimura (1988), Aoki and Nakamura (1988), Inokuchi et al.

a) Dept. Earth Sciences, Faculty of Science, Toyama University, Japan
3190, Gofuku, Toyama, 930-8555 Japan
b) National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Japan

* corresponding author
The purpose of this study is to develop a new method to investigate the transportation of debris avalanche by rockmagnetism. The method will also provide important information to explicate the mechanism of large-scale landslides and the prevention of disaster from the active volcanoes.

2. Rockmagnetic method

2.1 Remanent magnetization

Rocks and sediments generally contain iron oxide minerals such as Fe₂O₃, Fe₃O₄. They are called magnetic minerals because they can acquire the remanent magnetization recording the geomagnetic field: declination, inclination and field intensity. In the case of erupted volcanic material, the remanent magnetization is regarded as the fossil of geomagnetic field during the cooling process (Fig. 1). The geomagnetic pole positions for the ages of the layers of boring cores and the Okinajima debris deposit (younger than a million years), has not been different from the present pole. Further, there has been no tectonic event causing the large-scale deformation and/or rotation seen in the north-east Japan during the period (Otofuji et al., 1985). Accordingly, we can discuss the movement of rock mass at the collapse of the Bandai Volcano through the study of remanent magnetization.

2.2 Cleaning of the secondary overprinted magnetization

Volcanic materials acquire the remanent magnetization at the formation. The secondary magnetization is generally overprinted later on. To elucidate the original magnetization by eliminating the secondary magnetization, demagnetization experiment is conducted by the alternating magnetic field method and the thermal heating. Zijderveld diagram (Zijderveld, 1967) in Fig. 2 is used to analyze the change in direction and intensity of magnetization vector by the demagnetization. In this diagram, the magnetization vector is decomposed to vertical and horizontal components, then both the components are projected together. Here, the horizontal magnetization component is represented by filled circle, while the vertical component (projection to
Hideo SAKAI and Takashi INOKUCHI: Rockmagnetic study on the debris avalanche deposits of Bandai Volcano

2.3 Magnetic susceptibility and its anisotropy property

Magnetic susceptibility ($\kappa$) is the characteristic of the capacity of magnetization in the sample. It is studied by the measurement of induced magnetization ($J$) under the artificial magnetic field ($H$); the relation is expressed as $J = \kappa H$.

The susceptibility (induced magnetization) of the natural material shows frequent directional anisotropy, that is, the presence of the easy axis and the difficult axis of magnetization. This feature is called the anisotropy of magnetic susceptibility (AMS). AMS appears depending on the alignment of magnetic minerals in the sample.

Shape and grade of AMS are studied by the analysis of AMS ellipsoid and its principal axes, where the amplitude of the principal axes (maximum, intermediate and minimum) is represented as $K_{\text{max}}$, $K_{\text{int}}$, and $K_{\text{min}}$, respectively. The AMS data are plotted in the Flinn-type diagram (Fig. 3: Flinn, 1962) with the ordinate axis of $K_{\text{max}}/K_{\text{int}}$ and the abscissa axis of $K_{\text{int}}/K_{\text{min}}$. Anisotropy shape related to foliation and lineation is particularly examined in this diagram. Regarding the alignment of magnetic minerals as the representative of mineral alignment in the sample, AMS analysis is used to study the sedimentary condition of the subaquous deposit (e.g. Sakai et al., 2001), the flow direction of the igneous rock and also the erupted area of the volcano (Tarling and Hrouda, 1993).

2.4 Application of paleomagnetism and rockmagnetism in this study

The remanent magnetization memorizes the three components (declination, inclination, intensity) of geomagnetic field at the formation of strata, which will be reserved as the fossil of geomagnetic field. Due to the rotation during boring, declination data of the core are generally useless, however, we can examine whether the inclination data are identical with the past geomagnetic inclination at the formation. The inclination difference is, then available to estimate the transportation and the settling process of the landslide block, especially when a large-scale block movement occurs. Anisotropy of magnetic susceptibility is also useful to reconstruct the block movement through the arrangement of magnetic minerals in the samples.

3. Samples and Experimental procedure

Fig. 4 shows the locations of borings BD1, BD2, BD 3 and the sampling site 14 at the outcrop of Okinajima debris avalanche. BD 1 is the furthest from the crater, situate at the lower portion of the 1888 collapse area within the avalanche valley. BD 2 is located at the end of collapse area and BD 3 is in the center of collapse area. BD 4 and BD 5 in the map are the other boring sites where the Okinajima and Zunashi debris avalanches were investigated. The paleomagnetic results on these two cores are described by Sakai et al. (2003).

Samples for rockmagnetic study were prepared by selecting long core segments of at least 10-30 cm, making certain that there was no misplacement with respect to the top and bottom of cores. Several cylinder samples of 1 inch diameter and 1 inch length were prepared from each segment (Fig. 5).

Magnetization of each sample was studied by ring-core type spinner magnetometer (SMM85) and cryogenic magnetometer (2 G 760R). Magnetic susceptibility was measured by MS-2 magnetometer and the anisotropy of magnetic susceptibility was investigated by KLY-3 S Kappabridge apparatus.
4. Results of boring cores

4.1 Stability of remanent magnetization

In Fig. 6, stability of remanent magnetization of samples taken from the core is examined. Demagnetization experiment shows that in most samples, remanent magnetization is stable and secondary magnetization can be eliminated by low level demagnetization.

The Thellier’s method and the progressive thermal demagnetization method (Sakai and Hirooka, 1986) were also applied on several samples of BD1. The results of these experiments indicate that the remanent magnetization has a thermal origin.

In the following discussion, the remanent magnetization after applying the appropriate level of alternating field and/or thermal demagnetization is used.

4.2 Paleomagnetic inclination of boring cores

4.2.1 BD1 Core (depth of 100m, located at the lower portion of 1888 collapsed area)

Lithofacies and magnetic inclination data (sampling points) are shown in Fig. 7A. It is suspected that the 1888 deposit of debris avalanche is accumulated at a depth shallower than 21.2m (Tanaka et al., 1995), with the underlying layer consisting of a volcanic sequence with lithified pyroclastic flow deposits, andesitic and basaltic lava. In the upper region of the 1888 debris deposit, samples for rockmagnetic study are collected from the andesitic lava and the volcanic breccia in the pyroclastic flow deposits.

1888 rock debris originated from Pliostocene volcanic formation of Ko-Bandai Volcano (Mimura and Nakamura, 1995). In the northern side of Mt. Bandai, there are no debris avalanches prior to 1888 collapse and after the formation of Ko-Bandai Volcano. Ko-Bandai Volcano comprises mainly lava flows and pyroclastic flow deposits. These eruption products have acquired the thermal remanent magnetization at the formation and maintained the magnetization as the fossil of geomagnetic field before their movement at the 1888 collapse.

Inclination throughout the core is 50-65 degrees (the upper most section is 45 degrees), and does not deviate appreciably from the geomagnetic inclination of the site area. Based on the results of thermal demagnetization, the possibility that the debris deposit remagnetized after reaching the present location is low. Taking the concentrated inclinations of debris avalanche deposit into consideration, it is concluded that the debris avalanche (depth of 21.2m) was transported to BD 1 site as a block during the collapse, in the 1888 phreatic eruptions.
4.2.2 BD 2 Core (depth of 209m, located at the end of 1888 collapsed area)

Lithofacies and magnetic inclination data are shown in Fig. 7B. The zone down to 80.8m depth from the surface contains the debris avalanche deposit associated with the 1888 collapse, where the rocktypes of the studied samples are andesitic lava and the volcanic breccia.

Debris avalanche deposits have the concentrated magnetic inclination of 60 to 75 degrees, it is suggested that, in the vicinity of BD 2 site, the 1888 debris avalanche of 80.9m depth was transported as a block without significant internal deformation.

Magnetic inclination of the debris avalanche deposit is 10-15 degrees steeper than the inclination of underlying layer. This difference in inclination indicates that the block of debris avalanche moved to the location BD2, and rested on the existing slope. Horizontal rotation of debris block during the sliding may also cause the inclination difference. Tanaka et al. (1995) have suggested the possibility that the debris avalanche of BD 2 core may have deposited at the slope based on a study on the thickness of debris around BD 2 site. Fig. 8 illustrates the possible movement of debris avalanche to explain the inclinations of BD 2 core.

4.2.3 BD 3 Core (depth of 100m, located in the center of 1888 collapse area)

Lithofacies and magnetic inclination data are shown in Fig. 7C. According to Sekiguchi et al. (1995), the drilling site of BD 3 is at a central part of the 1888 caldera walls which collapsed along a length of about 600 m in 1954 and accumulated at the bottom of caldera. That is, the surface of BD 3 core consists of the layer of 1954 collapse. From the area of debris avalanche deposit below to a depth of 23.7m, discrete samples from andesitic lava and volcanic breccia are studied.

Most of the samples from the surface layer show the unstable magnetization. After eliminating the unstable data, two samples of the debris avalanche deposit show the inclination of c.a. 10 degrees, which differs...
greatly from the inclinations of debris avalanche in BD 1 and BD 2 cores. The underlying layer with tuff and highly fractured andesitic lava also has the remanent magnetization with scattered inclination.

It indicates that the debris avalanche and the underlying volcanic layer (depth of 100m) had been severely fractured, at BD 3 in the center of the collapse area.

Based on results of three cores, we conclude that the large block of debris avalanche deposit has slid down to BD 1 and BD 2 sites without significant internal deformation, following the 1888 eruption of Bandai Volcano. The sliding is 1-2 km from the center of col-
4.3 Anisotropy of magnetic susceptibility for BD 2 core

Shape anisotropy of magnetic susceptibility was analyzed by the Flinn-type diagram in Fig. 9. Foliation type anisotropy is dominant for the samples of debris avalanche deposit. It suggests that the 1888 debris avalanche deposit at BD 2 site is not deformed significantly, which is concordant with the conclusion derived from the remanent magnetization in 4.2.2.

Fig. 10 (B) shows the variation in the magnitude of magnetic susceptibility with depth for BD 2 core. Susceptibility of debris deposit is systematically higher than that of underlying sequence and there is a clear boundary at 80.8m depth. Together with the magnetic inclination change in Fig. 10 (A), the rockmagnetic study supports the suspected boundary in the core between 1888 debris avalanche and the underlying layer. Difference in the magnitude of susceptibility may be related to that the 1888 debris avalanche deposit hav-
ing been derived from the Old and New Bandai Volcanoes, while the underlying layer consists of the volcanic sequence of Pre-Bandai Volcano (Tanaka et al., 1995).

Fig. 10 (C) shows the declination difference between the directions of AMS maximum axis and remanent magnetization. Since the core has been rotated horizontally while drilling, we decided to correct the rotation angle by referring the declination of remanent magnetization. Declination of AMS maximum axis thus calculated shows the concentrated direction for debris avalanche deposit to be around N30-45W. This direction may be related to the formation of volcanic layer as the source of the 1888 debris avalanche before collapse.

5. Magnetism of Okinajima debris avalanche deposit

In order to investigate the block transportation of debris avalanche deposit, magnetization of the Okinajima debris avalanche deposit was studied. This debris avalanche is associated with Okinajima collapse, the largest rock slide avalanche among those identified on Bandai volcano (Mimura, 1988; Moriya, 1988). Based on the topographic characteristics, the debris avalanche deposit with an estimated volume of 4 cubic km covers over 50 square km from Okinajima to the western portion of Kitakata (Inokuchi et al., 1988). The deposit that can be observed is few ten of meters thick and is composed entirely of rock debris of Old Bandai Volcano.

At Bandai-cho Futo in Fig. 4 (Site 14), located about 5 km from the crater, there is a huge hummocky hill of Okinajima debris avalanche deposit which is 20m high and 80m wide. The exposure shows a highly fractured basalt lava with the matrix consisting of fine rock debris. We collected 8 samples at random, within a 40m wide, from the fractured basalt lava and the volcanic breccia in the matrix of the outcrop area for rockmagnetic study. Each sample was orientated with the clinometer, so that both declination and inclination of remanent magnetization are available for discussion.

In Fig. 11, Schmidt equal-area projection of magnetic direction of samples following the thermal demagnetization at 540°C is shown. Due to the removal of secondary magnetization by the demagnetization treatment (such as shown in the Zijderveld diagram), the magnetic directions of the samples become concentrated. There is no systematic difference in the magnetic direction between the lava blocks and matrix materials. Additionally, it was determined by the Thellier’s method that the magnetization is thermal in origin.

Remanent magnetizations of the samples are in southwest declination with low inclinations, which deviates from the geomagnetic field. What follows is the interpretation for the studied outcrop. The magnetization was originally oriented in the same direction as the geomagnetic field where the volcano was formed. However after the Okinajima collapse, the rock mass was transported as block (hummocky hill) and the orientation of remanent magnetization was shifted accordingly.

Based on the rockmagnetic study, it is demonstrated that even the hummocky hill of debris avalanche with a height of 20m and a width of 80m, transported 5 km survived as a mega block without significant internal deformation. A similar mechanism as in the above discussion was suggested for the hummocky hill of Nirasaki debris deposits at Yatsugatake Volcano by Mimura et al. (1982). They expressed the situation as “Mega rock blocks were coffee cups floating down a stream”.

Sakai et al. (2003) studied the rockmagnetism of Okinajima debris found in the BD 4 and BD 5 cores. The results indicate that the block of Okinajima debris with thickness over 100m has been transported about 2 km from the crater without severe internal deformation. Combining with the analyzed data of the outcrop at Site14 and those of boring cores including the 1888 debris avalanche and Okinajima debris deposits, we propose that the boring cores at the site near the crater and the outcrop of hummocky hill at a far distance from the crater are both useful and important objects in the investigation of block transportation of debris avalanche deposit by rockmagnetism.

In this rockmagnetism study, we showed the block transportation event to occur at several debris avalanche deposits, however, as such events may not occur normally, further studies should be conducted on other cases to understand the conditions of occurrence of block movement for the debris avalanche deposits.

6. Conclusion

(1) Rockmagnetic studies were conducted on three boring cores drilled at the bottom of north wall of Bandai Volcano. The cores are BD 1 in the avalanche valley at the lower portion of 1888 collapse, BD 2 at the edge of collapse site, and BD 3 at the center of collapse. Magnetic inclinations of the debris avalanche deposit in BD 1 and BD 2 are concentrated and not very different from the geomagnetic inclination. Following conclusion is obtained. The 1888 debris avalanche initiated
Hideo SAKAI and Takashi INOKUCHI: Rockmagnetic study on the debris avalanche deposits of Bandai Volcano

during the phreatic eruptions and the collapse of Bandai Volcano, reached the BD1 and BD2 sites with little internal deformation and was deposited gliding as blocks. At BD2 site, the block settled on the existing slope.

The magnetization of debris avalanche deposit and underlying layer in BD3 scattered and derived from geomagnetic inclination. It indicates that the layer in the vicinity of BD3 has been subjected to severe fracturing and redeposition up to a depth of a 100m.

(2) Direction of AMS maximum axis for the debris deposit of BD2 shows N30-45W. This direction may be the fossil of flow direction of volcanic material before the collapse, which is important for the study of the source area of debris.

(3) Magnetization of hummocky hill (20m high and 80m wide), from Okinajima debris avalanche shows the concentrated direction with deviated azimuth from the geomagnetic field. It indicates that the large block of hummocky hill has been transported 5 km while retaining its structure at the volcanic formation. The phenomena is similar to the study on Nirasaki debris hummocky hill by Mimura et al. (1982).

This study proves the rockmagnetic method to be useful for investigation of transportation and depositional process of debris avalanches as a large landslide event. We are planning to apply the method on the debris avalanches of other volcanoes, and also on the general landslides.

Acknowledgements

We would like to thank Dr. Koji Mimura, Dr. Tatsuo Sekiguchi and the late Dr. Kohei Tanaka for providing the data and for their suggestions about the geology, petrology and topography of the areas under investigation.

References


Mimura, K., Kawachi, S., Fujimoto, U., Taneichi, M., Himukai, T.


