Magnetic fabric stratigraphy of a thick rhyolite lava flow

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Abstract: In order to illustrate vertical and horizontal variations in the anisotropy of rock fabrics, particularly in highly viscous silicic lavas, we used anisotropy of magnetic susceptibility (AMS) measurements to investigate a thick rhyolitic lava flow with clearly marked flow structures. We describe the relationships between the geometry of the flow structures and the evolution of magnetic fabrics. Material was taken from three drill cores, located at different distances from the eruptive source. The dips of the AMS foliation planes agree with structural measurements taken throughout the section and with increasing distance from the source. This evolution corresponds to the transition flow structure geometries from stubby to lenticular and further to tabular. All of the flow structure geometries present oblate AMS fabrics, which is a characteristic deformation feature of rhyolitic lava flows.

Keywords: rhyolite lava, flow structure, anisotropy of magnetic susceptibility, drill cores.

Introduction

Rhyolite is a common volcanic rock in continental regions. It has been known to possess stable magnetization acquired at the time of its formation (Wilson, 1963) and has contributed, for example, to constructing a reference paleosecular variation curve (Robertson, 2007). However, the use of rhyolite lavas for accurate description of the geomagnetic field direction at the time of their formation may be problematic. Paleomagnetic direction distributions, even those from a single rhyolite dome, sometimes contain outliers. For example, Grindley et al. (1994) reported Pleistocene (750 ka) directions from a rhyolite lava dome: one of six remanence directions was similar to an expected paleomagnetic direction for the same region, but the others exhibited large scatter.

One factor of major concern in the distortion of remanence direction is flow structure, which is a texture ubiquitous to rhyolite lavas. Uno et al. (2013) pointed out that large deflections of paleomagnetic direction occur at stratigraphic positions where high volume fractions of light-colored banding are observed. Viewed microscopically, flow structures (i.e., light-colored banding) are composed of aggregates of extensively deformed minute cavities (high porosity zone, Furukawa and Uno, 2015), and therefore such structure may provide the space to accommodate deformation and compaction, leading to large deflection of the remanence.

The attitude of flow structures in rhyolite lava develops irrespective of the horizontal plane and, accordingly, may not be used as a structural attitude for tilt correction (Hagstrum and Lipman, 1986). In addition, the attitude varies with depth in the flow and with distance from the source of the lava (Smith and Houston, 1994). Thus, it is important to quantify the spatial distribution of flow banding in rhyolite lava flows using an appropriate method in order to establish how the patterns of flow banding predict the type of distortion of remanence directions. Anisotropy of magnetic susceptibility (AMS) presents the ideal method, because AMS fabrics mimic the structure of flow banding in viscous, silicic lava flows (Cañón-Tapia and Castro, 2004).

The flow structure is described as high porosity zone, which consists of interconnected minute cavities with a porosity of 40–50 vol% (Furukawa and Uno, 2015). The high porosity zone is generated by cavitation soon after extrusion of the lava from the vent (Smith et al., 2001; Furukawa and Uno, 2015), and develops to stretched thin band due to flow-induced shear through the course of lava flowing. This process occurs at any stratigraphic position even in a thick rhyolite lava flow. Therefore, stratigraphy of a rhyolite lava flow using AMS taken at multiple sections effectively illustrates the development of internal structures of the rhyolite lava.

The Takanoobane rhyolite lava of Aso volcano in Japan (reported by Furukawa and Kamata, 2005) is a thick rhyolite lava flow with clearly marked flow structure. The lava has been penetrated completely by three drill corers, data from which are used in this study. These
three cores were drilled at different distances from the source and are expected to provide an opportunity to observe vertical and horizontal variations in the anisotropy of the rock fabric. Here, we delineate both vertical and horizontal inhomogeneous changes in rock magnetic fabrics in a rhyolite lava, based on fabric analysis using the AMS measurements.

Takanoobane rhyolite lava

The Takanoobane rhyolite lava was erupted at Aso caldera on Kyushu Island, Japan (Fig. 1a) and forms a dome-like structure. The lava has been dated using the K–Ar method to give an age of $51 \pm 5$ ka (Matsumoto et al., 1991), and its volume is estimated to be $0.14$ km$^3$ (Miyabuchi et al., 2004). The bulk rock chemistry of the lava is $70–71$ SiO$_2$ wt% (Miyoshi et al., 2005). The source of the lava is situated on the top of the dome-like structure ($32^\circ53'7.77''N$, $131^\circ0'23.85''E$) (Fig. 1b). We examined three continuous drill cores that completely penetrated the Takanoobane rhyolite lava (cores AVL1, AVL2, and AVL4) provided by the Aso Volcanological Laboratory of Kyoto University. The lava exhibits thicknesses of $91.4$ m, $91.0$ m, and $54.5$ m in cores AVL1, AVL2, and AVL4, respectively; these cores were located $230$ m, $340$ m, and $120$ m away from the source in the horizontal direction, respectively.

The Takanoobane rhyolite lava in the three cores is composed of an inner crystalline part and marginal glassy parts (upper and basal glassy layers) (Furukawa et al., 2010) (Fig. 1c). The inner crystalline part exhibits a well-defined flow structure, characterized by light-colored bands a few millimeters to $3$ cm thick. Microscopic observation revealed that the light-colored bands are defined by the high porosity zone consisting of aggregates of deformed minute cavities that are $5–50$ μm in diameter (Furukawa et al., 2010; Furukawa and Uno, 2015). The geometry of the flow structure is generally lenticular and tabular in cores AVL1 and AVL2, respectively. In core AVL4, clear flow banding is not discernable but shows stubby configuration of high porosity zone (hereafter for simplicity, it is also referred to as flow structure).

Ten samples of the inner crystalline rhyolite from core AVL1, twenty-one samples from AVL2, and five samples from AVL4 were collected to prepare specimens with diameters of $25$ mm and lengths of $22$ mm (Fig. 1c); however, some samples from cores AVL1 and AVL2 were exhausted by previous experiments (Uno et al., 2013), such that nine samples from core AVL1 and eighteen samples from AVL2 were analyzed in this study.
study (Fig. 1c). The AMS data of the rhyolite lava of core AVL2 were previously reported by Furukawa and Uno (2015). To describe vertical and horizontal variations in the anisotropy of rock fabrics in the rhyolite lava, we arranged the dataset of principal axes directions and Jelínek parameters \( P \) and \( T \) (Jelínek, 1981) together with the attitude of internal geological structures of the lava from the three cores. The cores were divided into 1-m sections for storage and were not azimuthally oriented. Therefore, we arbitrarily defined the dip direction of the flow structure for each sample as having an azimuth of 0° (i.e., the north).

The dip of the flow structure of samples is clearly measurable for cores AVL1 and AVL2 and measured to be 20–34° and 10–48° for cores AVL1 and AVL2, respectively (Fig. 2), while that for core AVL4 is rather obscured. The dip of the flow structure in core AVL2, in particular, appeared to decrease with stratigraphic position below the ground level, with dips of 35–48° and 10–25° in the upper and lower parts of the crystalline rhyolite, respectively. Furukawa and Kamata (2005) attributed the difference to the ramp structure.

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We have arranged the AMS data of the three cores, consisting the principal axes directions and Jelínek parameters \( P \) and \( T \). The \( K_{\text{max}} \) axis of core AVL1 is generally of north to northeast declination, while that of cores AVL2 and AVL4 is generally of west to northwest or east declination (Fig. 3, Table 1). The \( K_{\text{max}} \) axis for all

**Fig. 2.** Dips of the flow structures as a function of core depth. Solid and open symbols represent data from cores AVL1 and AVL2, respectively.

**Fig. 3.** Equal-area projections of the principal magnetic susceptibility axes on the lower hemisphere. Data from core AVL2 are from Furukawa and Uno (2015). Solid squares, triangles, and circles represent maximum, intermediate, and minimum axes, respectively. The minimum axis directions for core AVL2 are divided into two groups: directions for samples taken from between 32 and 58 m depth below ground level with intermediate inclinations ranging between 32° and 56°, and directions for samples taken from between 62 and 86 m depth below ground level with steep inclinations ranging from 66° to 76°.
the cores has shallow inclination mostly less than 20°. In all the cores, the plane defined by the $K_{\text{max}}$–$K_{\text{int}}$ axes (AMS foliation plane) dips northward and that the $K_{\text{min}}$ axis dips southward; the plane dips by 0–26°, 14–58°, and 14–53° for cores A VL1, A VL2, and A VL4, respectively. Careful examination of the $K_{\text{min}}$ axis directions from core A VL2 allowed the recognition of two groups of orientations, which can be explained by the difference in core depth between the two groups (Furukawa and Uno, 2015). The $K_{\text{min}}$ axis directions for samples deeper than 60 m below the ground level (samples from 32 to 58 m depth) exhibit intermediate inclinations in the range 32–56°, while those shallower than 60 m below the ground level (samples from 62 to 86 m depth) exhibit steep inclinations in the range 66–76° (Fig. 3).

The degree of anisotropy ($P_\ell$) and the shape parameter ($T$) were compared between samples of cores A VL1, A VL2, and A VL4. The $P_\ell$ values for all the cores generally vary within the range 1.05–1.10 throughout the lava section; in detail, the fluctuation for core AVL2 is rather large (Fig. 4a). The $T$ values for core AVL1 generally fluctuate between approximately 0.5 and 1.0, and no significant depth-dependent fluctuations are observed (Fig. 4b). In contrast, the $T$ values for core AVL2 appear to increase with stratigraphic position below the ground level. Deeper than 70 m below the ground level, the values for core AVL2 are obviously large (mostly around 0.9). The $T$ values for core AVL4 shows the largest fluctuation, but no significant depth dependence is observed. The $P_\ell$–$T$ diagram shows that most of the $T$ values for all the core display scattering in the area corresponding to oblate fabric (Fig. 4c). The studied lava, at least in its crystalline part, is generally characterized by the oblate deformation features.

We compared the dip of the plane of the flow structure with the dip of the AMS foliation plane, using the data for cores AVL1 and AVL2 (Figs. 4d and 4e). The examination of the relationship between dip values of the two planes is meaningful, because both planes have similar dip directions; the plane of the flow structure has a dip direction of 0° (definition), and the AMS foliation plane dips northward (Fig. 3). No significant correlation is present between the two values for core AVL1 (Fig. 4d). In contrast, for core AVL2, the dips of these planes agree well at each stratigraphic level (Fig. 4e), despite the fact that the dips vary within a range of ~10–60° throughout the lava section and show a large change at depths around 60 m below the ground level.

Core AVL1 is 230 m from the source of the lava, while core AVL4 is 120 m from the source. Core AVL2 is 340 m from the source and located within the path of the main lava flow toward southwest (Fig. 1b). The spatial distribution of flow structure of the studied lava is summarized in Fig. 5. The structure develops from a

### Table 1. AMS data for cores AVL 1 and 4.

| Sample position below the ground level (m) | $K_{\text{max}}$ | $K_{\text{int}}$ | $K_{\text{min}}$ | $L$ | $F$ | $P_\ell$ | $T$ | Dip of magnetic foliation |
|------------------------------------------|------------------|------------------|------------------|-----|-----|--------|-----|--------------------------|
|                                           | $D$ ($^\circ$) | $I$ ($^\circ$) | $D$ ($^\circ$) | $I$ ($^\circ$) | $D$ ($^\circ$) | $I$ ($^\circ$) | $D$ ($^\circ$) | $I$ ($^\circ$) |
| core AVL1                                 | 39               | 60               | 9                | 328 | 13  | 184    | 75  | 1.014 | 1.058 | 1.078 | 0.597 | 15  |
|                                           | 44               | 51               | 17               | 316 | 18  | 182    | 65  | 1.003 | 1.072 | 1.085 | 0.915 | 25  |
|                                           | 48               | 3                | 16               | 273 | 0    | 184    | 75  | 1.009 | 1.041 | 1.053 | 0.642 | 15  |
|                                           | 54               | 60               | 13               | 328 | 11   | 199    | 72  | 1.016 | 1.044 | 1.063 | 0.463 | 18  |
|                                           | 57               | 345              | 5                | 75   | 6    | 210    | 82  | 1.014 | 1.046 | 1.064 | 0.518 | 8   |
|                                           | 64               | 65               | 5                | 334  | 11   | 180    | 79  | 1.010 | 1.051 | 1.066 | 0.678 | 11  |
|                                           | 67               | 11               | 15               | 281  | 0    | 192    | 76  | 1.005 | 1.053 | 1.065 | 0.835 | 14  |
|                                           | 70               | 66               | 10               | 331  | 24   | 178    | 64  | 1.013 | 1.044 | 1.061 | 0.530 | 26  |
|                                           | 74               | 30               | 0                | 300  | 0    | 243    | 90  | 1.018 | 1.047 | 1.068 | 0.447 | 0   |
| core AVL4                                 | 12               | 83               | 4                | 347  | 53   | 176    | 37  | 1.022 | 1.046 | 1.070 | 0.337 | 53  |
|                                           | 13               | 288              | 11               | 20   | 9    | 150    | 76  | 1.014 | 1.068 | 1.090 | 0.643 | 14  |
|                                           | 15               | 272              | 9                | 11   | 42   | 173    | 47  | 1.031 | 1.022 | 1.054 | -0.164 | 44  |
|                                           | 18               | 302              | 10               | 39   | 35   | 198    | 54  | 1.025 | 1.046 | 1.073 | 0.278 | 36  |
|                                           | 21               | 5                | 41               | 273  | 2    | 180    | 49  | 1.001 | 1.034 | 1.040 | 0.918 | 41  |

$K_{\text{max}}$, $K_{\text{int}}$, and $K_{\text{min}}$: the maximum, intermediate, and minimum axes of AMS, respectively.

$D$ and $I$: declination and inclination, respectively.

$L$, $F$, $P_\ell$, and $T$: lineation, foliation, degree of anisotropy, and shape parameter, respectively.

Data for core AVL2 can be found in Furukawa and Uno (2015).
Fig. 4. (a) Degree of anisotropy $P'$ and (b) shape parameter $T$ (Jelinek, 1981) as a function of core depth. (c) Shape parameter $T$ versus degree of anisotropy $P'$. Solid circles, open circles, and cross signs denote data from cores AVL1, AVL2, and AVL4, respectively. When the $T$ value is positive (negative), it indicates oblate (prolate) fabrics. (d, e) Plot of the dip of the plane of AMS foliation and the dip of flow structures as a function of core depth.
stubby shape near the source of the lava, which corresponds to where core AVL4 was drilled (Furukawa and Kamata, 2005), but develops to a lenticular shape that corresponds to where core AVL1 was drilled. In turn, this lenticular shape develops into a tabular geometry, which corresponds to where core AVL2 was drilled. All the stubby (AVL4), lenticular (AVL1), and tabular (AVL2) geometries of flow structure provided the oblate AMS fabrics (Fig. 4c), irrespective of distance from the lava source.

The oblate deformation regime in the rhyolite lava flow is consistent with previous observations. Castro et al. (2002) and Befus et al. (2015) investigated obsidian lava flows in the United States based on the distribution of microlite orientations in the lava and argued that the lava body, as well as the vent, experienced a large component of pure shear strain, leading to oblate fabrics. Merle (1998) performed an analogue modelling showing the dominance of pure shear component within the lava. In our study area, Furukawa and Uno (2015) observed a photomicrograph of a plane cut parallel to the flow structure of a sample (54 m below the ground level of core AVL2). The photomicrograph shows that microlites are aligned in the plane and parallel to the AMS $K_{\text{max}}$ directions, illustrating the pure shear dominated flow and associated oblate deformation.

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Koji Uno conceptualized the study, conducted sampling, made laboratory measurements, analyzed data, and wrote the manuscript.
Kuniyuki Furukawa conceptualized the study, conducted sampling, analyzed data, and wrote the manuscript.