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Instantaneous record of the geomagnetic field direction of various facies from pyroclastic flow deposits: Tests for consistency in paleomagnetic directions

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ABSTRACT

A comparative study of the paleomagnetism of various lithofacies of pyroclastic flow deposits has been undertaken to examine the accuracy of their remanent magnetization direction at the time of deposition. The Aso-2 pyroclastic flow deposit, which erupted at 141 ka from Aso caldera, Japan, was chosen as the site of our investigation because the deposit formed over a short time period and the paleomagnetic directions of the deposit are expected to record substantial contemporaneous volcanism. Paleomagnetic samples of densely welded, lava-like rheomorphic, and non-welded pyroclastic deposits were collected at nine sites from the Aso-2 pyroclastic flow deposit. Remanence directions from densely welded pyroclastic deposits display good within- and between-site consistency and are considered to accurately record the ambient geomagnetic field direction at the time of emplacement. Rheomorphic pyroclastic deposits had directions that show good within-site consistency, and it is considered that this material obtains its remanence direction parallel to the ambient field corresponding to the time of its emplacement. Remanence directions from non-welded pyroclastic deposits show large confidence limits or deviations from their expected directions. Such deposits would likely be prone to modification of remanence direction introduced from random rotations of remanence-carrying material during syn- or post-depositional stages. In conclusion, we suggest that among various lithofacies of pyroclastic flow deposits, remanence directions observed from non-welded pyroclastic deposits may need to be interpreted cautiously.

1. Introduction

Volcanic rocks are generally recognized as a useful source of information regarding ancient geomagnetic fields. Volcanic rocks have contributed, in particular, to constructing reference curves of paleosecular variation due to their ability to preserve instantaneous records of the geomagnetic field direction at the time of their formation (e.g., Hagstrum and Champion, 2002). In the case of historical lava flows, the accuracy of their remanent magnetization direction is ascertained by comparing the directions from lava flows with the expected direction provided by the International Geomagnetic Reference Field (IGRF) model (Finlay et al., 2010).

Pyroclastic flow deposits are explosive volcanic eruption products, from which it was believed that consistent paleomagnetic directions were observable from both vertical and horizontal perspectives (e.g., Dalrymple et al., 1965). However, the use of pyroclastic flow deposits for an accurate description of the geomagnetic field direction at the time of their formation is not always successful. Zanella et al. (2001) reported Pleistocene to Recent (49–8 ka) directions from welded to weakly welded scoria; one of four scoria deposits was found to show inclinations 25–30° divergent from the contemporaneous paleomagnetic direction of the same region. Alva-Valdivia et al. (2005) presented Pliocene (ca. 5 Ma) directions from welded scoria deposits and claimed that such deposits may be a reliable indicator of the ancient geomagnetic field direction; however, this is based upon consistency among observed directions, which turned out to be different from the expected direction. Hoblitt et al. (1985) reported on the remanent magnetization direction from non-welded pyroclastic material of an historical eruption (1980 Mount St. Helens Eruption)

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and recognized disagreement between the observed and expected directions. Rosenbaum (1986) presented Miocene (ca. 14 Ma) paleomagnetic data from a thick ash flow deposit and observed internal variation in remanence direction up to about 40° from a densely welded part of the flow. Although the abovementioned discrepancy in remanence direction is addressed by the authors and is partially accounted for by tectonic movement or secular variation, a full explanation must also include syn- or post-depositional deformation of the deposit itself, namely deformation during stages of loading or deformation in metastable, loosely packed deposits, respectively.

There has been no attempt to perform a comparative study of paleomagnetic directions from various lithofacies of pyroclastic flow deposits whose remanence directions are expected to be essentially identical. The Aso-2 pyroclastic flow deposit, which erupted at 141 ka from Aso caldera, Japan, was chosen as the site of our investigation. This deposit merits discussion because it is made up of various lithofacies of pyroclastic flow deposits, ranging from non-welded to rheomorphic characteristics (Ono et al., 1977). The Aso-2 pyroclastic flow deposit has been interpreted as having formed over a very short time period because there is no evidence of any hiatus (Ono, 1965; Watanabe and Ono, 1969). The paleomagnetic directions of the deposit are expected to be in close agreement with each other, as all directions record substantial contemporaneous volcanism. In addition, welded tuffs of the Aso-2 pyroclastic flow deposit show very steep (nearly 80°) paleomagnetic inclination according to previous studies (Fujii et al., 2002; Takai et al., 2002; Mochizuki et al., 2013). This would minimize the influence of rock fabrics on remanence directions; a remanence direction nearly perpendicular to the paleohorizontal plane is not easily influenced by deviating the remanence vector from the ambient field toward the anisotropic, paleohorizontal plane. This enables us to evaluate the possible control of the emplacement mode of various pyroclastic deposits on remanence directions (i.e., plastic deformation by welding and rheomorphism, or possible rotation of non-welded clasts). Previous paleomagnetic data for Aso-2 deposit were solely obtained from densely welded lithofacies. Here, we examine the accuracy of the remanent magnetization direction of a pyroclastic flow deposit. Material of a high-fidelity geomagnetic field recorder is elucidated through comparison of paleomagnetic direction among various lithofacies of pyroclastic flow deposit.

2. Geological setting and sampling

Aso volcano is located in Kyushu Island, Japan (Fig. 1a). It is the second largest caldera in Japan, which measures 25 km (north–south) × 18 km (east–west) (Fig. 1b). The caldera was formed incrementally by four major eruptive events, namely, Aso-1 (266 ± 14 ka), Aso-2 (141 ± 5 ka), Aso-3 (123 ± 6 ka) and Aso-4 (89 ± 7 ka) (Matsumoto et al., 1991), collectively referred to as the Aso pyroclastic flow deposit. The total volume of the pyroclastic flow deposits is estimated to be 175 km^3 (Matsumoto, 1963).

Aso-2 deposits are composed of welded to non-welded basaltic to dacitic pyroclastic material (Ono, 1965; Koyaguchi and Iguchi, 1994) and divided into four major subunits: Aso-2R, Aso-2A, Aso-2B, and Aso-2T in ascending order (Fig. 1c) (Ono et al., 1977). Aso-2R is composed of basaltic to andesitic, intensely welded pyroclastic flow deposits, and exhibits rheomorphic features, which resulted in homogeneous lava-like lithofacies (Ono and Watanabe, 1974). Aso-2A consists of densely welded dacitic pyroclastic flow deposits. Aso-2B is composed of non-welded to densely welded, basaltic to andesitic scoria and pyroclastic flow deposits. Aso-2T is formed from andesitic scoria fall deposits.

A paleointensity study of Aso-2 deposits provided low paleointensity of 22.9 ± 1.6 μT and the corresponding virtual dipole moment (VDM) of 3.11×10^{22} A m^2 (Mochizuki et al., 2013), determined by the double heating technique of the Shaw paleointensity method combined with low temperature demagnetization (LTD–DHT Shaw method, Tsunakawa and Shaw, 1994; Yamamoto et al., 2003). This VDM values is, however, relatively higher than that for geomagnetic excursions during the last 300 kyr determined by the same method ($0.6–2.2 \times 10^{22}$ A m^2, Mochizuki et al., 2006; Yamamoto et al., 2010). Aso-2 deposits were dated at 141 ± 5 ka (Matsumoto et al., 1991), which is not consistent with the established excursion events that are close to the age of Aso-2 formation, namely, the Blake excursion between 116 and 112 ka and the Iceland Basin excursion at about 188 ka (Channell, 2006; Osete et al., 2012). Accordingly, Takai et al. (2002) referred to an excursion-like event recorded in Aso-2 deposits as the Aso event. Recently, Mochizuki et al. (2013) reinterpreted this as a geomagnetic field at the beginning or end of a geomagnetic excursion event.

Paleomagnetic samples of densely welded pyroclastic deposits were collected at four sites (19B, Aso-2B; 74, Aso-2A; 75A, Aso-2A; 79, Aso-2A). Rheomorphic pyroclastic deposits were collected at two sites (19R, Aso-2R; 75R, Aso-2R). Non-welded scoria clasts were collected at two sites (19S, Aso-2B; 76, Aso-2B). Non-welded ash was collected at one site (74N, Aso-2B). These deposits are hereafter referred to as the following three categories of lithofacies: densely welded pyroclastic deposits (sites 19B, 74, 75A, and 79), rheomorphic pyroclastic deposits (sites 19R and 75R), and non-welded pyroclastic deposits (sites 19S, 74N, and 76). All samples are hand samples except for those from site 74N. Hand samples were oriented in the field with a tripod-mounted magnetic compass. Samples from site 74N were collected using aluminum pipes that had diameters of 25 mm and lengths of 22 mm, and were also oriented in the field using a tripod-mounted magnetic compass. The attitude of bedding planes or eutaxitic structures was nearly horizontal, except for one site (site 74) that showed an apparent dip of ~30° to the northeast. The nine sampling sites were distributed over an area covering ~30 × 30 km (Fig. 1b).

3. Methods

In the laboratory, core specimens measuring 25 mm in diameter and 22 mm in length were cored from each hand sample that was oriented in the field using a compass. Using the specimens, measurements of natural remanent magnetizations (NRMs), thermal demagnetization of a three-component isothermal remanent magnetization (IRM) (Lowrie, 1990), and preparation of polished thin sections were performed.

3.1. Paleomagnetism

NRMs were measured with a Natsuhara SMM-85 spinner magnetometer. All samples were subjected to progressive thermal demagnetization treatment using a Natsuhara TDS-1 thermal demagnetizer in a series of 50 °C steps between 100 and 500 °C, and in steps of 20–30 °C above 500 °C. Results for each specimen were plotted on orthogonal vector diagrams (Zijderveld, 1967) to evaluate their demagnetization behaviors (Fig. 2). Principal component analysis was used to estimate the direction of the observed magnetic components (Kirschvink, 1980).

3.2. Rock magnetism

3.2.1. Thermal demagnetization of a three-component IRM

Thermal demagnetization of a three-component IRM was performed on selected samples with an ASC Scientific pulse magnetizer to identify ferromagnetic mineral components. IRMs