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Variation of rock magnetic properties during the 1991–1995 eruption at Unzen, Japan

Naoko UENO*, Setsuya NAKADA**

Abstract

Magnetic properties were investigated using samples taken within a few days after eruption events through the latest eruption at Unzen Volcano, Kyushu Japan, with additional lava and bomb samples taken a few years after the events. Natural remanent magnetization, Curie temperature, coercive force, coercivity of remanence and remanent saturation magnetization imply occurrence of four periodical changes, showing temporal increase within each period superposed with gradual increase throughout the whole period of the eruption. One of the boundaries of the four periods is supported by the petrological study on the same samples taken within a few days (Nakada and Motomura, 1999), which reflected two pulses of lava effusion rate.

Key words: rock magnetism, hysteresis, Unzen Volcano

1. Introduction

The eruption and its associated activities of Unzen Volcano between 1991 and 1995 were continuously observed and reported in detail in wide area of geoscience, for instance, volcanology, seismology, petrology or geoelectricity. In this study, we carried on extensive rock magnetic measurements of magnetic hysteresis, thermomagnetic analysis, thermal and alternated field (AF) demagnetization of natural remanent magnetization (NRM) and thermal demagnetization of isothermal remanent magnetization (IRM) on the same samples for which petrological observation were reported by Nakada and Motomura (1999) and few additional samples. This study suggests that changes in petrological signatures may be observed through variations in rock magnetic characters.

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Table 1  NRM, initial susceptibility, Tc and hysteresis parameters.
Number of order corresponds with the order of time of eruption represented by months from May '91 in the third column.
* Samples collected a few years after the deposit

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2. Sampling

Unzen volcano had erupted producing dacitic lava lobes forming a dome on the summit. Fifteen lava samples (all samples except marked with * in Table 1) were taken from the youngest deposits within a few days after deposition near the summit. Some samples were taken directly from parts of exogenous lobes with clearly-known eruption date. The sample No. in the Table 1, represents sampling date. Chronology of the eruption was overviewed by Nakada et al. (1999). Petrology of all the samples except NU931202 was described in Nakada and Motomura (1999). Outline of lava dome (Fig. 1) was appeared in the geological map of Unzen Volcano (Watanabe and Hoshizumi, 1995).

The other lava samples marked with * in Table 1 were taken a few years after deposition. NU9106 is a bomb deposited in the eruption of June 1991 collected at Muhyozawa, 1 km distant from the lava dome. NU9410 is glassy lava in Senbongi pyroclastic flow, 4 km distant from the lava dome produced in June 1993. No. 951017#11 was collected from lobe numbered 11 which might have deposited early 1994. NU9705-1, -2, -3 were collected at the summit after the end of the eruption. NU9705-2, -3 were collected from the closest point to the last lobe. All the samples were collected without directional orientation to the present geomagnetic field.

3. Methodology

Magnetic hysteresis and the analysis of magnetization-temperature at high magnetic field (Js-T or thermomagnetic analysis) were carried out using a vibrating
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Fig. 1 Outline of lava dome.
Large and small numbers show the eruptions center and the distribution of each lava dome or lobe respectively (by S. Suto appeared in Watanabe and Hoshizumi, 1995)
Colored by the author (Ueno).

sample magnetometer (VSM) made by Riken-denshi. Cross-checks on some typical samples were done by with Micro-mag VSM in Kyoto University. Weight of the specimens varied from 0.2 to 0.4 gram. Js–T curves were obtained both in air and in vacuum of $10^{-4}$ Pa with a magnetic field of 1 T (tesla) between room temperature and 650°C. It took 6 hours for heating and cooling.
Specimens weighed from 1 to 4 gram for AF demagnetization.
For thermal demagnetization, heating and cooling were performed in air. Samples weighed from 0.6 to 2.9 gram.
IRM acquisition was carried out with up to 1 T field produced by the magnet of VSM. IRM in 70 mT field was induced perpendicular to the pre-induced IRM in 1 T (SIRM) for typical samples. Thermal demagnetization up to 600°C was followed.
All the specimens were irregular in shape.

4. Results

J–T curve: Results from the VSM measurement are summarized in Table 1. All of Js–T curves show single Ti-poor titanomagnetite phase both in air and in vacuum (Fig. 2). Averaged Curie temperature ($T_c$) in vacuum for 1991–1992 specimens is 429°C, 450°C for 1993 specimens and 492°C for 1994–1995 specimens. Averaged $T_c$
in year is increased from the beginning to the end of the eruption. Averaged $T_c$ measured in air is 42°C higher than that in vacuum. Sufficient oxygen in air accelerated oxidation to increase the $T_c$ through the experiment.
Fig. 3 Examples of hysteretic loops.

*Hysteresis parameters*: Typical examples of loop are shown in Fig. 3. Almost all are narrow in shape reflecting the low coercive force (Hc), which is the characteristic of multidomain magnetic minerals. In Day diagram (Day et al., 1977), most
of the specimens are plotted in multidomain (MD) region of magnetite, although a few are suggestive of pseudosingle domain (PSD) or coexistence of single and multidomain regions (Fig. 4). All the specimens plotted in the PSD region were collected after 1993. We decided to divide the time of eruption into four periods: 1991–Jan. 1992, Mar. 1992–Dec. 1992, 1993 and 1994–1995 according to cyclic variation of hysteretic characters obtained from the samples taken from the youngest deposits within a few days after deposition near the summit (Fig. 5). In Fig. 5, it is shown that the hysteretic parameters of Hc, Hcr, Mr, and NRM have the trend to increase with time and change in one cycle. Time variation of saturation magnetization (Ms) and initial susceptibility measured by Birtington instrument are not clear, but seem to have inverse correlation with other hysteretic parameters and NRM. In Fig. 6, the trend in Day diagram is clearly shown with the same samples as Fig. 5, to move from coarse to fine grain in a cycle.

*Thermal demagnetization of NRM*: In Fig. 7, results of thermal demagnetization with the directional change are shown for two samples. Fig. 7(a) is the sample of the early stage in the first cycle (1991.6), while the other (Fig. 7b) is the last stage sample in the second cycle (1992.12). The higher medium destructive temperature and the larger stability in direction are the characteristics of the last stage sample compared with the early stage sample.

*AF demagnetization of NRM*: All the samples collected within a few days after eruption events have the median destructive field (MDF) between 10 mT and 35 mT. Some of the samples taken a few years after the events have the MDF of over
Fig. 5 Time variation of NRM, initial susceptibility and hysteretic parameters for samples taken within a few days after eruption event.

Fig. 6 Day diagram in each stage of eruption for samples taken within a few days after eruption event.

50 mT. These samples contain more stable magnetite than the samples collected soon after deposit. As illustrated in Fig. 8, the results of AFD show the same characteristics as the thermal demagnetization: the latter stage sample (921229)
Fig. 7 Directional change in THD of NRM (Demag Level: °C)
910612b: The early stage sample
921229: The late stage sample
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Fig. 8  Directional change in AFD of NRM (Demag Level: oe).
910612b: The early stage sample
921229: The late stage sample

has the higher MDF and the smaller deviation in directional study compared with the early stage sample (910612b). The comparison of AF demagnetization curves with various grain size reported Argyle et al. (1994) shows that the shape of the demagnetization curve changes according to the grain size. The demagnetization curve of the latter stage sample in this study shows the finer grain size than that of the early stage sample, because the apparent grain size changes smaller in the latter stage due to oxidation during cooling. Normalized THD and AFD curves of typical samples are shown in Fig. 9.

Isothermal remanent magnetization (IRM): All the samples in the acquisition of IRM, saturation attained at less than 200 mT (Fig. 10). Re-experiment for the typical three samples (Fig. 11a) shows that the sample which acquired IRM with the higher intensity in Fig. 10 (NU9705–2) is rich in higher coercive component. Thermal demagnetization of IRM was performed on the typical three samples by a method modified from Lowrie test (Lowrie, 1990), in which two components were acquired for 1 T and 0.07 T orthogonally, and thermally demagnetized (Fig. 11b, c, d). Fig. 11b and Fig. 11c clearly show that blocking temperature spectrum is
different between the two components. Component with the lower coercive component (<70 mT) is characterized by the lower blocking temperature. Component with the higher coercive component (>70 mT) that may be characterized by the higher blocking temperature. The higher coercive component is dominant in sample with the higher intensity of SIRM (Fig. 10, Fig. 11c).

5. Discussion

In this study, it is found that magnetic characteristics in Unzen lavas change
cyclically. Based on this cycle, it is possible to divide the eruption into four periods. The previous petrological study by Nakada and Motomura (1999) reported the cyclic eruption during 1991–1995 defined by temporal change in magma effusion rate and dome height (Fig. 12). They also reported the evidences of slow cooling at low effusion rate, increase of groundmass crystalinity, low Fe–Ti oxide temperature, low porosity. Most of the boundaries of the cyclic change of magnetic characters found in this study seem correspond with the magma supply, effusion rate and dome heights which were already reported. The boundary between the first and second periods indicated by the rock magnetic properties is not supported petrologically. The next boundary is in the end of 1992, just corresponding to the boundary between the first and the second pulses of magma supply. The last boundary is in the end of 1993, in harmony with the start of endogenous growth by which lava dome was elevated. At the time of the rapid elevation of dome, the main magnetic minerals were of multidomain size as indicated by small Hc, Hcr and NRM. At the end of the periods, dome elevation almost stopped because magma elevated very slowly. Accordingly, dome lava cooled slowly and oxidized adequetly. The oxidation created ilmenite in magnetite and made the effective domain of magnetite smaller, and decreased Ti content in magnetite. Decreasing of Ti in magnetite rises Tc (Akimoto, 1962). The oxidized titanomagnetite has a similar effect as small magnetite and resulted to increase Hc (Larson et al., 1969), Hcr, Mr and NRM. Also, it works domain size to move from multi-domain region to pseudo-single domain region in Day diagram.

As seen in Fig. 12, effusion rate decreased from 1991 to 1995 as a whole. Slow cooling of lava at the time of low effusion rate resulted magnetite to be smaller in
Fig. 11  IRM experiments of typical samples.
(a) IRM acquisition curves of typical samples.
(b) Thermal demagnetization of IRM of No. 920601.
(c) Thermal demagnetization of IRM of No. 921229.
(d) Thermal demagnetization of IRM of No. NU9705-2.
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Fig. 12 Temporal change in magma effusion rate and dome height during 1991–1995. (Nakada and Motomura, 1999) Colored by the author (Ueno).

effective domain size and poorer in Ti content as mentioned above. As a result, averaged $T_c$, $H_c$, $H_{cr}$, $M_r$ and NRM increased through the eruption as a whole.

6. Conclusions

By the change of rock magnetic characters during the eruption, eruption at Unzen 1991–1995 was divided into four periods with correspond mostly to the the change in magma effusion rate and dome height reported by Nakada and Motomura (1999). $T_c$, NRM, $H_c$, and $H_{cr}$, $M_r$ were increased, and domain size changed
to smaller from multi-domain to pseudo-single domain region in Day diagram both within one period and through the eruption according to the increase of cooling time of lava or the change of oxygen fugacity and temperature of lava.

Acknowledgements

Prof Y. Tanaka of Kyoto University guided to take samples Nos. NU9106 and NU931202. NU9410 was sampled at the guided tour held by the Volcanological Society of Japan. NU9705-1, -2, -3 were collected at the guided tour held by Unzen International Workshop: Decade Volcano and Scientific Drilling. Dr. Zhong Zheng of Sogokaihatu Co. supported the IRM experiment. Prof M. Funaki of NIPR helped in microscopic observation of magnetic minerals. Prof N. Ishikawa of Kyoto University measured some samples with Micro-mag for crosscheck. Prof M. Kono of Okayama University and Prof H. Tanaka of Kochi University gave suggestions to improve the manuscript. This research was supported by a Grant-in-Aid from Toyo University.

References

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要 旨

上野直子・中田篤也：雲仙普賢岳（1991〜1995）の噴火時期による溶岩の磁性変化

雲仙普賢岳（1991〜1995）の噴火では噴火中の雲仙普賢岳頂上で押し出された溶岩が次々に新しいドームを作っていた。ドームの形状観察から溶岩の噴出量がわかる、その時間あたりの量がマグマの噴出率として報告されている。本研究ではドームの観察者（中田）が新しくドームに加わった溶岩を2、3日中に採取した試料を主に、数年後に採取された試料も加えてその磁化特性の時間変化を研究した。

自然残留磁化の初期曲線、熱消磁、交流消磁、ヒステリシス、熱磁化曲線、キュリー点、保磁力、残留保磁力、飽和磁化、飽和残留磁化を求める実験を行った。非履歴残留磁化の獲得およびその熱消磁実験を行った。

熱磁化曲線は真空中と空気中で測定したが、真空中のキュリー点は平均で1991〜1992年は429℃、1993年は450℃、1994〜1995年は492℃で噴火が始まっているの時間経過と共に高くなっている。空気中では200℃で42℃高かった。キュリー点の値から主な磁性鉱物はチタンマグネタイトであることがわかる。チタンマグネタイトのキュリー点はチタンの量が増すると高くなる。300〜400℃で緩やかに鉄が酸化しても、高めに400℃以上で急に酸化（高温酸化）しても高くなる。自然残留磁化は高温酸化で増加しやすい、今回は平均的には時間と共に自然残留磁化は増加しており、時間がたつにつれて高温酸化の条件になったと考えられる。また、酸素分圧が高いと、より高温酸化しやすい。

高温酸化すると鉄の多いチタノマグネタイト相とチタンの多い相（イルメノヘマタイト）に分かれて、鉄の多い相が磁化の担い手になりキュリー点が高くなる。高温酸化時にはイルメノヘマタイトの生成でチタノマグネタイトが細分されて单磁区構造の大きさに近づく。化学組成が変わらない場合は、ヒステリシスから飽和残留磁化／飽和磁化の比をとると、単磁区から多磁区に変化するにつれて比の値は減少することが知られている（Day Diagram）。多磁区と単磁区では単磁区構造のほうが保磁力や自然残留磁化が高い。今回の試料は飽和残留磁化／飽和磁化の比と保磁力が時間と共に増加している。このに対し、今後の噴火では高温酸化により、磁化を担う鉱物の化学組成が時間と共に変わるとともに磁性鉱物が多磁区的構造で単磁区的構造に変化する方向にあり、両方の効果で磁気特性が変化したと考えられる。


岩石の磁気特性は温度や酸素分圧に敏感に反応する。磁気特性を火山噴火の研究にもっと利用していきたい。