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Paleomagnetic study of rhyolitic lavas in Kozu-shima Island, Japan.

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神津島の流紋岩質溶岩の古地磁気学的研究

中井睦美

1. Introduction

Kozu-shima Island is one of the Izu islands situated southern part of the Tokyo Prefecture, Japan (Fig.1, Lat. : 34° 15', Log. : 139° 7 '). Kozu-shima Island is a volcano. Almost rocks in the Izu islands are basalt, but Kozu-shima Island and Nii-jima Island have rhyolitic lavas. We have collected Pleistocene-Holocene rhyolitic lava and baked silt samples in Kozu-shima Island, and have studied paleomagnetism of them.

Paleomagnetism of basaltic rocks has been well studied (Garnier *et al.*, 1996 ; Hagstrum and Champion, 1994 ; 1995 ; Kosterov, 2001 ; Pick and Tauxe, 1993 ; Ellwood, 1978 ; Wasilewski, 1969 ; Matuyama, 1929 ; Ozima and Larson, 1968), because basaltic lava rocks are valuable to study paleomagnetism and paleointensity. Basaltic magma is not sticky, and basaltic lava flow is very flat and horizontal during flowing, depositing and cooling. Therefore, paleomagnetic directions obtained from basaltic rocks are stable and useful for reconstruction of ancient geomagnetic direction.

On the other hand, paleomagnetism of rhyolitic rocks in volcanic islands has been not well studied, because rhyolitic lavas are very sticky, so they deposit slantingly. Therefore, the paleomagnetic directions of rhyolitic lava flows are considered not to be useful for reconstruction of ancient geomagnetic direction. Actually, NRMs (Natural Remanent Magnetizations) of Kozu-shima Island's samples, do not point the north direction that is geomagnetic pole direction. It is considered that the rhyolitic lavas moved several times during cooling and depositing, because the rhyolitic magma was gammy and became hard at high temperature.

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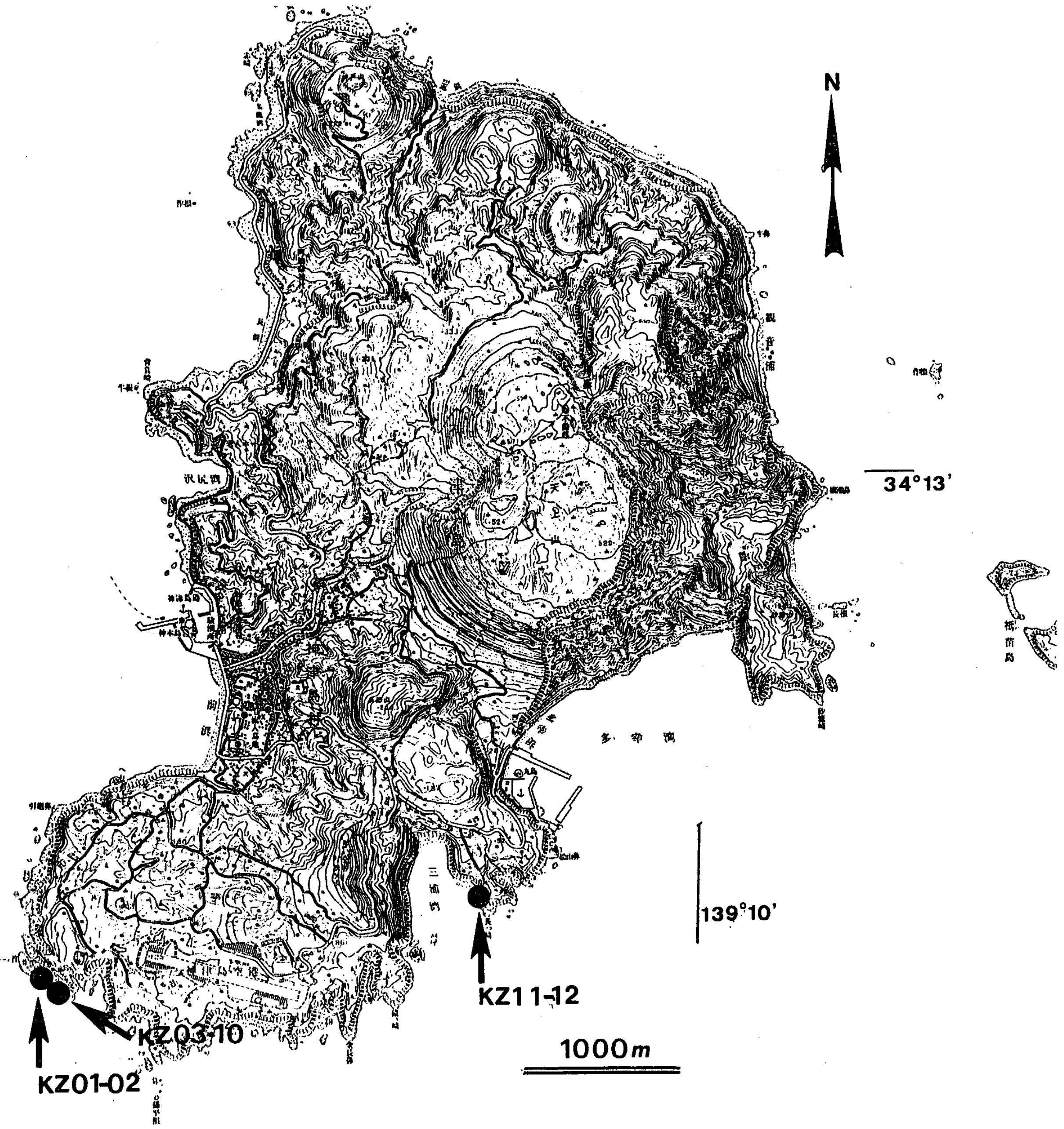


Fig.1 The sampling area of Kozu - shima Island. KZ01-02 : hypersthene rhyolitic lava obtained from "Lava Flow of Membo volcano", KZ03-10: baked silt and peperite including rhyolite of "Lava Flow of Membo volcano", KZ11-12 : glassy biotite rhyolite obtained from "Lava Dome of Matsuyamahana volcano".

It is sure that Kozu-shima Island's rhyolitic rocks remain paleomagnetic evidences that these lavas have moved several times. The paleomagnetic experimental results can show the thermal history of these rhyolitic lava flows in Kozu-shima Island, because PTRMs (Partial Thermal Remanent Magnetization) can add every temperature steps. ChRMs (Characteristics Remanent Magnetization) and PTRMs of samples were measured and analyzed in the laboratory of Toyo University. In this paper, the thermal history of some Kozu-shima Island's lavas, analyzed from the experimental results, is reported.

2. Geological background

Issiki (1982 in Japanese) has published the geological report and map of the Kozu-shima Island. The geological basement of Kozu-shima Island is adularized dacite lava which age is suggested during Miocene-Pliocene (?). These rocks distribute only very small area of northern coast of Kozu-shima Island. Over the basement, Pleistocene-Holocene rhyolitic lavas and pyroclastic deposits from monogenetic volcano, are distributed.

Kozu-shima Island's rhyolite are counted more than seventeen monogenetic volcanos and divided into two groups (Issiki, 1982 in Japanese). Older volcanoes usually consist of hypersthene rhyolite and cummingtonite rhyolite. Younger volcanoes are generally biotite rhyolite. But, relation between each lavas is not exactly known.

Older volcanoes are named “Lava flow of Membo volcano (hypersthene rhyolite)”, “Lava flow of Nagahama volcano (cummingtonite rhyolite)”, “Lava flow of Kannon'ura volcano (biotite rhyolite)”, “Lava flow of Hashiruma volcano (hypersthene rhyolite)” and “Lava flow of Sanukayama volcano (biotite bearing and cummingstonite bearing rhyolite)”. Younger volcanoes are named “Lava dome of 221m peak volcano (biotite rhyolite)”, “Lava dome of 262m peak volcano (hornblende bearing hypersthene rhyolite)”, “Lava dome of Nachisan volcano (biotite rhyolite)”, “Lava dome of Matsuyamahana volcano”, “Lava dome of Osawa volcano (biotite rhyolite)”, “Lava dome of Takodoyama volcano (biotite rhyolite)”, “Lava dome of Jogoyama volcano (biotite rhyolite)”,“Lava dome of Hanatate volcano (biotite rhyolite)”, “Lava dome of Ananoyama volcano (biotite rhyolite)” and “Lava dome of Kobeyama volcano (biotite rhyolite)”. Finery, lavas and pyroclastics of Tenjosan volcano erupted at 838A.D. Tenjosan volcano have formed the top of Kozu-shima Island, whose altitude is 571.5m.

The pyroclastic deposits in Kozu-shima Island consisted of pumice, lapilli, rhyolitic lithic fragments and ash, are named Chichibuyama pyroclastic deposits. They are covering wide area of Kozu-shima Island.

Some of these lavas near the seaside of this island, become hyaloclastite (volcanic rocks that flow into the sea at high temperature). Some the rhyolitic lavas are overviewed to be folding along the landform under lava (Photo.1). This folding is considered to form when these lavas flowed at high temperature. Silt chips was caught in the lavas when the lavas flowed over the surface of ground and over the seafloor. Sometimes these silt rocks had high temperature, so the silt rocks were drawn with lava. These rock facies are called peperite (Sakamoto, 1998, 2000 in Japanese). At Senryoike Pond situated in the southern part of Kozu-shima Island, Many peperites can be observed. Photo 2 is a hyaloclastite of rhyolitic lava flow. Photo 3 shows the silt rock caught in lava.

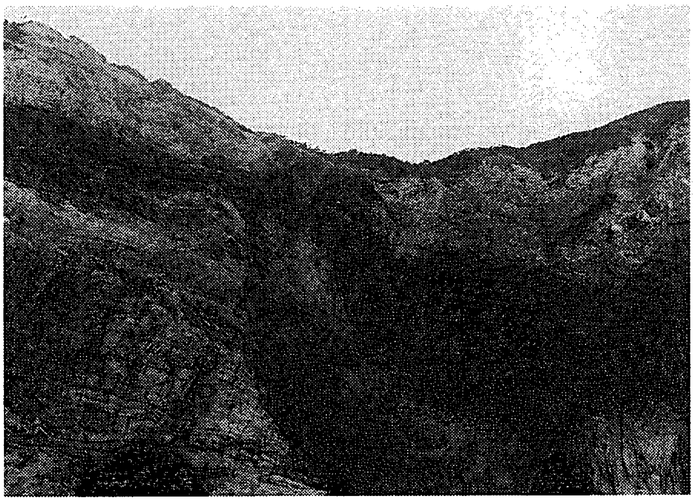


Photo.1 Folding of ryiolitic lava and hyaloclastite.

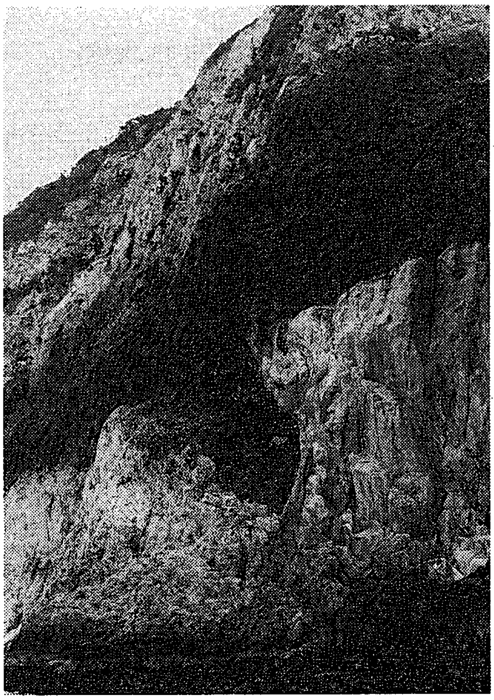


Photo 2 Upper black part is hyaloclastite of rhyolitic lava flow, underground is blocked ryholitic lava flow.

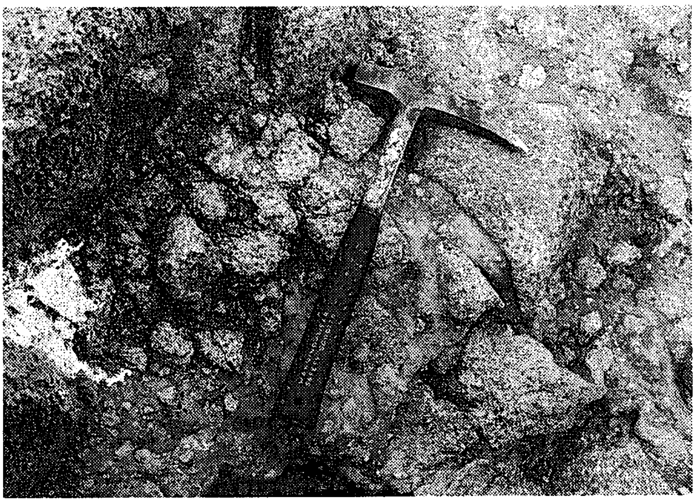


Photo 3 The silt rocks in "Lava Flow of Membo volcano".

Photo 4 Peperite in "Lava Flow of Membo volcano".

Photo 4 is a peperite.

3. Sampling

Samples for paleomagnetism were collected from “Lava flow of Membo volcano” (KZ01–10) and from “Lava dome of Matsuyamahana volcano” (KZ11, 12). These rocks are distributed in the southern part of Kozu–shima Island. The sampling points are shown in Fig.1. Both of KZ01 and 02 samples are glassy hypersthene ryolite, but KZ01 is hyaloclastite and KZ02 is lava flowing on the ground surface. KZ03–10 samples are baked silt rock. KZ03–6 and KZ8–10 are peperite, and KZ07 is a silt block in hyaloclastite. KZ11 and 12 are glassy biotite rhyolite. The reason to sample both silt rock and rhyolite, is to analyze how temperature these rocks have settled in now position.

Sampling method is hand sampling. At first, the arrows of strike and dip are marked on a flat plane of rocks. Next, collected samples are cut and grinded into a standard cubic sample, and label it with a “laboratory arrow” on it. We measure paleomagnetic data of these samples as if the “laboratory arrow” has been an N–direction.

Samples obtained from Kozu–shima Island, were made into a cube of about 1x1x1cm size. This cube size is too small for paleomagnetic research. Since width of silt part in peperite at studied area is very small, big size of cube as a 1x1x1inch cannot be cut out.

4. Method of experiments

Various NRMs (Natural Remanent Magnetization) of oriented samples cut from KZ01–12 were measured using spinner magnetometer. At first, NRM of row rock samples was measured. Next, we choose pilot samples carried out “stepped AF (Alternating fierld) demagnetization test”. This test can examine the stability of NRM. If NRM of rock is not stable, all paleomagnetic data is not significant.

After examination for NRM's stability, stepped thermal demagnetizations and steppwise PTRM magnetizations were carried out. This experiment is called Thellier method (Thellier and Thellier, 1959). It is a useful method to determine paleointensity of geomagnetic field. The law of additivity of PTRM is a foundation of Thellier method. PTRM that is acquired when samples cooled in a magnetic field below the Curie temperature, does not affect one of the original TRM. The relationship between the TRM and the field can be obtained by first measuring the NRM, by heating the sample to some temperature, for example 100℃, and cooling the sample in zero field (This is called thermal demagnetization). The sample is then reheated to the same temperature (100℃) but is cooled in a known field (of the order of the earth's magnetic field) and measured again (This is called PTRM remagnetization). This double heating procedure is repeated step by step until the highest unblocking temperature is reached.

We studied on Kozu-shima Island's samples using the same experiment of the Thellier method, but we do not expect to obtain paleointensity. The stepwise thermal demagnetization of the Thellier method shows thermal history of rocks, and PTRM remagnetization of the Thellier method shows the thermal magnetic property of rocks. Therefore, the Thellier method is appropriate experiment for our purpose. Thus, ChRMs after stepwise thermal demagnetizations and PTRMs acquired stepwise thermal remagnetizations through 50μT, were measured using the Thellier method. PTRM remagnetization and thermal demagnetization are similar in number of thermal steps. Temperatures of step are 20℃ (room temperature) 100℃, 150℃, 200℃, 240℃, 280℃, 320℃, 360℃,400℃, 430℃, 460℃, 490℃, 520℃, 540℃, 560℃,570℃ and 580℃. Constant time of max temperature is 20minutes.

5. Experimental results

Results of stepwise AF demagnetization test of the pilot samples show that magnetic remanence is stable and that NRM is useful for paleomagnetism. So, the cause of ChRM directions (NRMs after demagnetizations) change is rock body rotation.

In order to analyze thermal history and rock body rotation, we measured ChRMs and PTRMs. Figure 2, 3-(1)-(3), 4, 5 are intensity curve of ChRMs after stepwise thermal demagnetizations and of PTRMs acquired stepwise thermal magnetizations, vector direction traces of ChRMs and of PTRMs, and Zijderveld projections of thermal demagnetizations (Zijderveld, 1967).

Figure 2 is experimental results of rhyolite samples obtained from "Lava flow of Membo volcano" near the Senryoike Pond. KZ01 is hyaloclastite of rhyolitic lava flow and KZ02 is rhyolite lava. Figure 3 is experimental results of 10 baked silt samples obtained from peperite of "Lava flow of Membo volcano" near the Senryoike Pond. In these samples, we cut two cubic samples from KZ03 block, three cubic samples from KZ05, and one sample from each other blocks (KZ02, 04, 06, 08, 09, 10). Figure 4 is experimental results of silt samples including rhyolite of "Lava flow of Membo volcano" near the Senryoike Pond. Figure 5 is experimental results of rhyolite samples obtained from "Lava dome of Matsuyamahana volcano" at the eastern margin of the Miura Bay.

Intensity curve graph as Fig.3-(1) roughly explains blocking temperature (near Curie temperature) and paleointensity. Vector changes of demagnetized ChRM and remagnetized PTRM as Fig.3-(2) are shown on a sphere using Shumit net. ChRM curve of this graph shows the movement of rock bodies and PTRM direction goes to the direction of external magnetic field of 50μT at the highest temperature. Zijderveld projection shows intensity and direction of

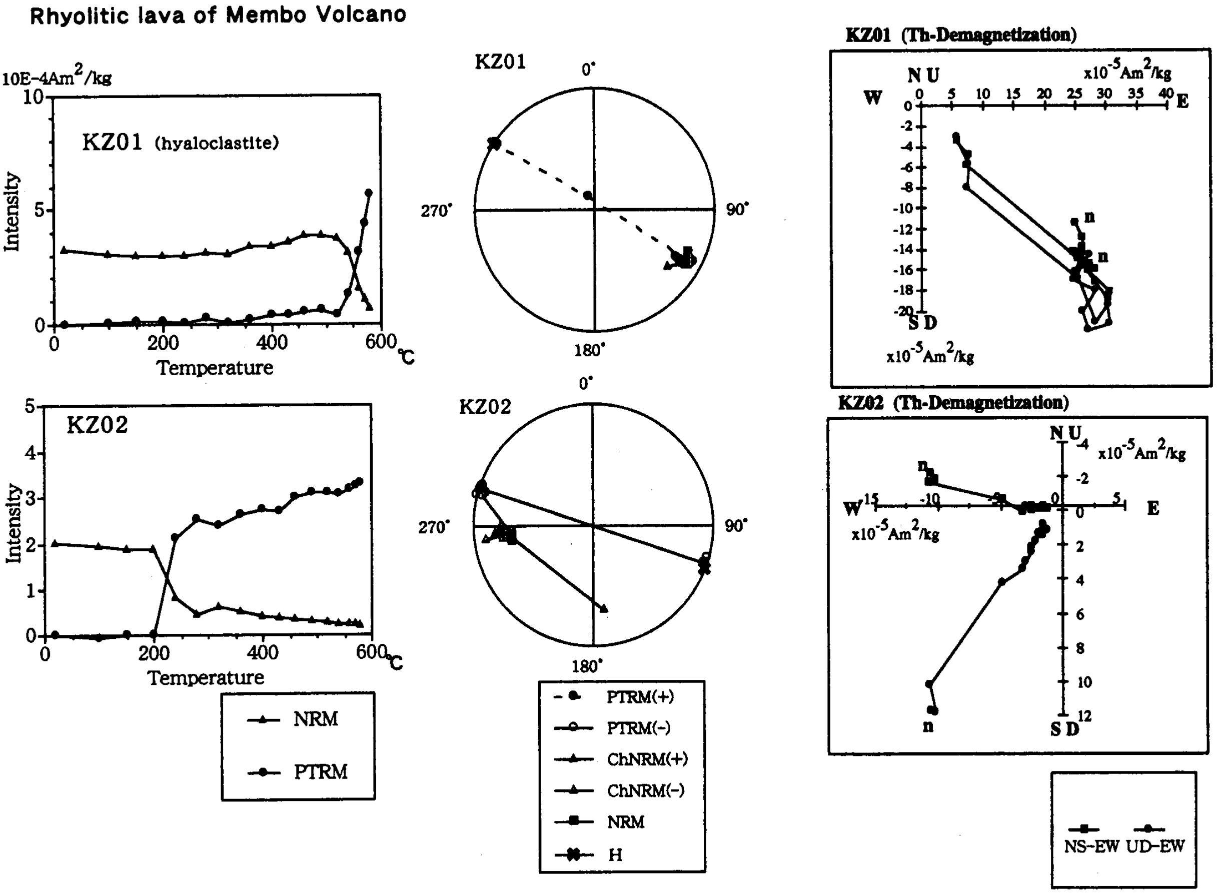


Fig.2 Experimental results of rhyolite samples obtained from "Lava flow of Membo volcano"near the Senry-oike Pond.

Left figures are magnetic intensities of PTRMs and of ChRMs. Central figures are the direction changes of PTRMs and of ChRMs. Right figures are Zijderveld projections of demagnetized ChRMs.

demagnetized ChRM vector, on a diagram as Fig.3-(3).

KZ01 data in Fig.2 shows that the source mineral of remanent magnetization is titanless magnetite, for Curie temperature is 580 ℃. This rock has high stability magnetization. Circumstantial observation of Zijderveld projection explains ChRM direction move at 400–430℃. This rock is hyaloclastite, so ChRM of natural thermal magnetization is acquired under rapidly cooling condition and settled temperature of rock bodies is suggested to be about 400–430℃.

KZ02 data in Fig.2 shows that Curie temperature of this rock is mainly 280℃ but secondary 580℃. From 150℃ to 580℃ ChRM direction of this rock is almost stable. Magnetization from room temperature to 150℃ is considered VRM (Viscous Remanent Magnetization) or CRM (alternating in low temperature). Trace of ChRM direction show that this rock body did not move below Curie temperature.

KZ03 data in Fig.3-(1) shows that silt part in peperite loses it's magnetization at 580℃ which is Curie temperature of the magnetite. The maximum intensity of remagnetized TRM is about two times as one of NRM. Other silt part samples (KZ04, 06, 08, 09, 10) in peperite have the same

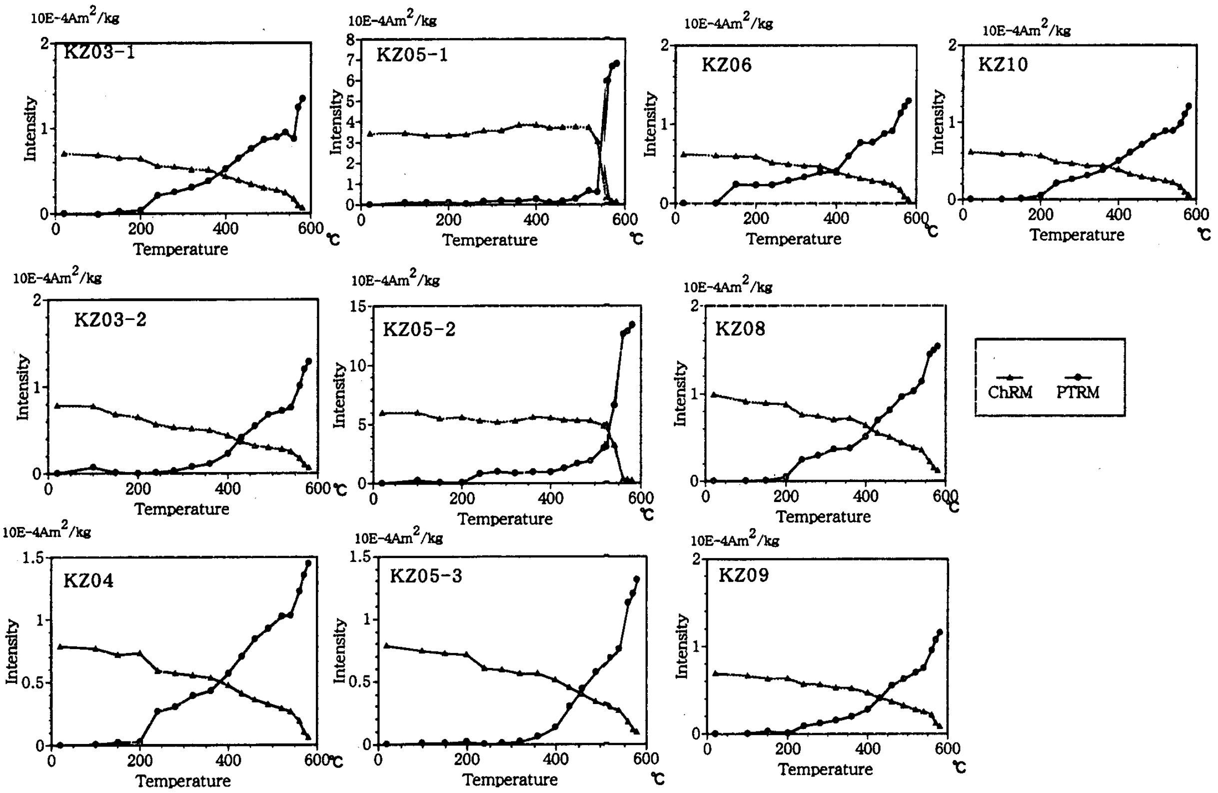


Fig.3—(1), Experimental results of ten baked silt samples obtained from peperite near the Senryoike Pond. Magnetic intensities of PTRMs and of ChRMs.

property as KZ03. On the other hands KZ05 have a Curie temperature of 560–570℃ that is slightly smaller than other silt samples in peperite.

Figure 3 –(2) is the direction change of demagnetized ChRM and remagnetized PTRM for silt part samples in peperite. Figure 3 –(3)is Zijderveld projection of demagnetized ChRM for silt part samples in peperite. These figures show peperite's ChRMs are almost stable, but demagnetization traces are not linier perfectly and have easy curves. We think these easy curves are caused small movement during cooling below Curie temperature. Zijderveld projection of some samples, for example KZ06, show secondary addition of VRM or CRM from 150 ℃ to room temperature. Moreover, Zijderveld projection of KZ05– 1 shows that trace changes at 560℃.We think this change is caused big movement of peperite brock at high temperature.

KZ07–1,2 data in Fig.4 shows that silt block in hyaloclastite of Menbo volcano loses it's magnetization at 580 ℃ which is Curie temperature of the magnetite. Maximum intensity of remagnetized TRMs is about two times as one of NRM. It is the same results as silt part in peperite. Other results are also the almost same as silt part in peperite.

KZ11 and 12 data in Fig.5 shows that the Curie temperature of Matsuyamahana volcano is 580℃, and the maximum intensity of remagnetized TRM is about 2–3 times as one of NRM. Both samples have secondary magnetization of VRM or CRM from room temperature to 150℃. It is remarkable

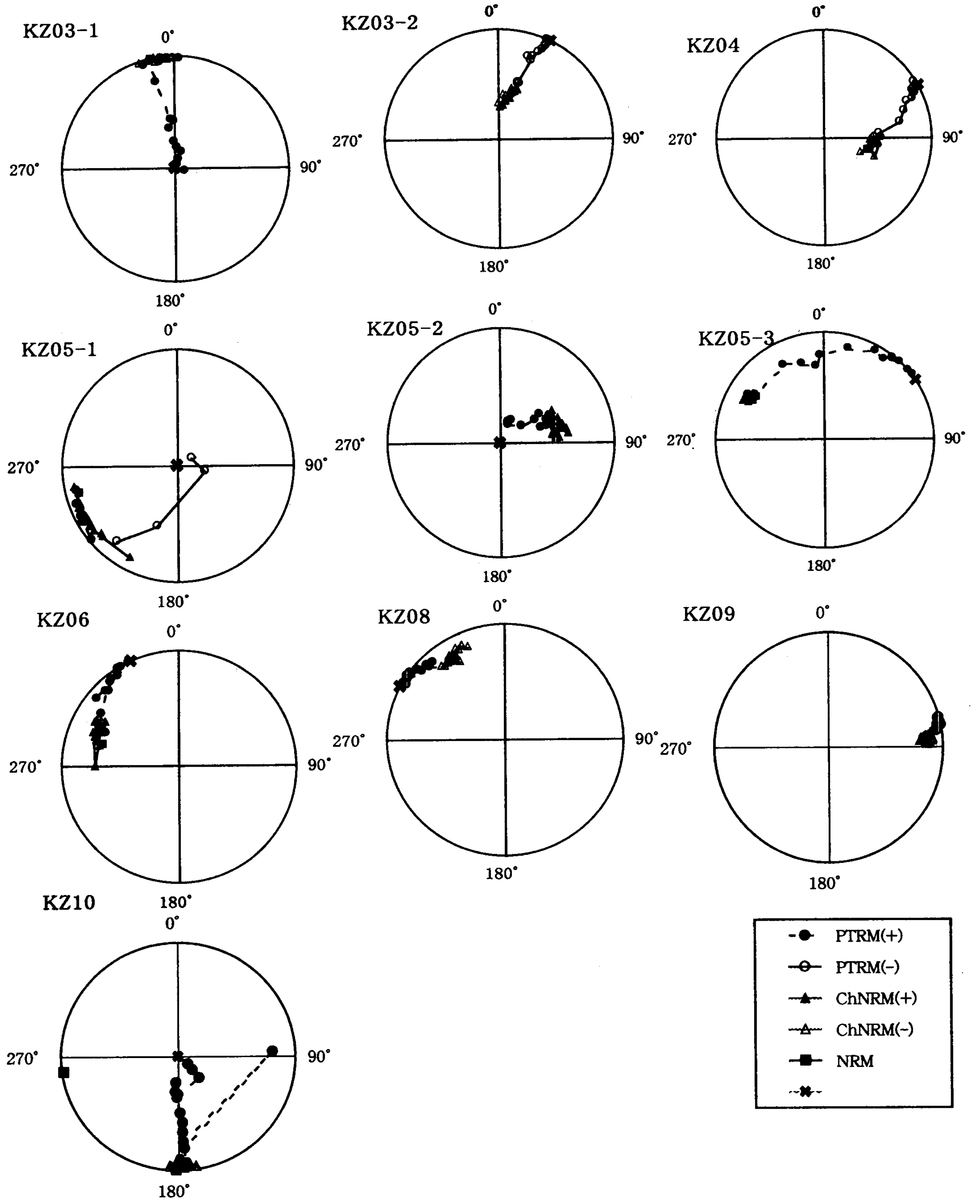


Fig.3— (2), Experimental results of ten baked silt samples obtained from peperite near the Senryoike Pond. The direction changes of PTRMs and of ChRMs.

that demagnetization traces on Zijderveld projection clearly curve at 460℃ or 490℃. We think this curve in demagnetization traces are caused large rotation of lava brocks at 460℃–490℃.

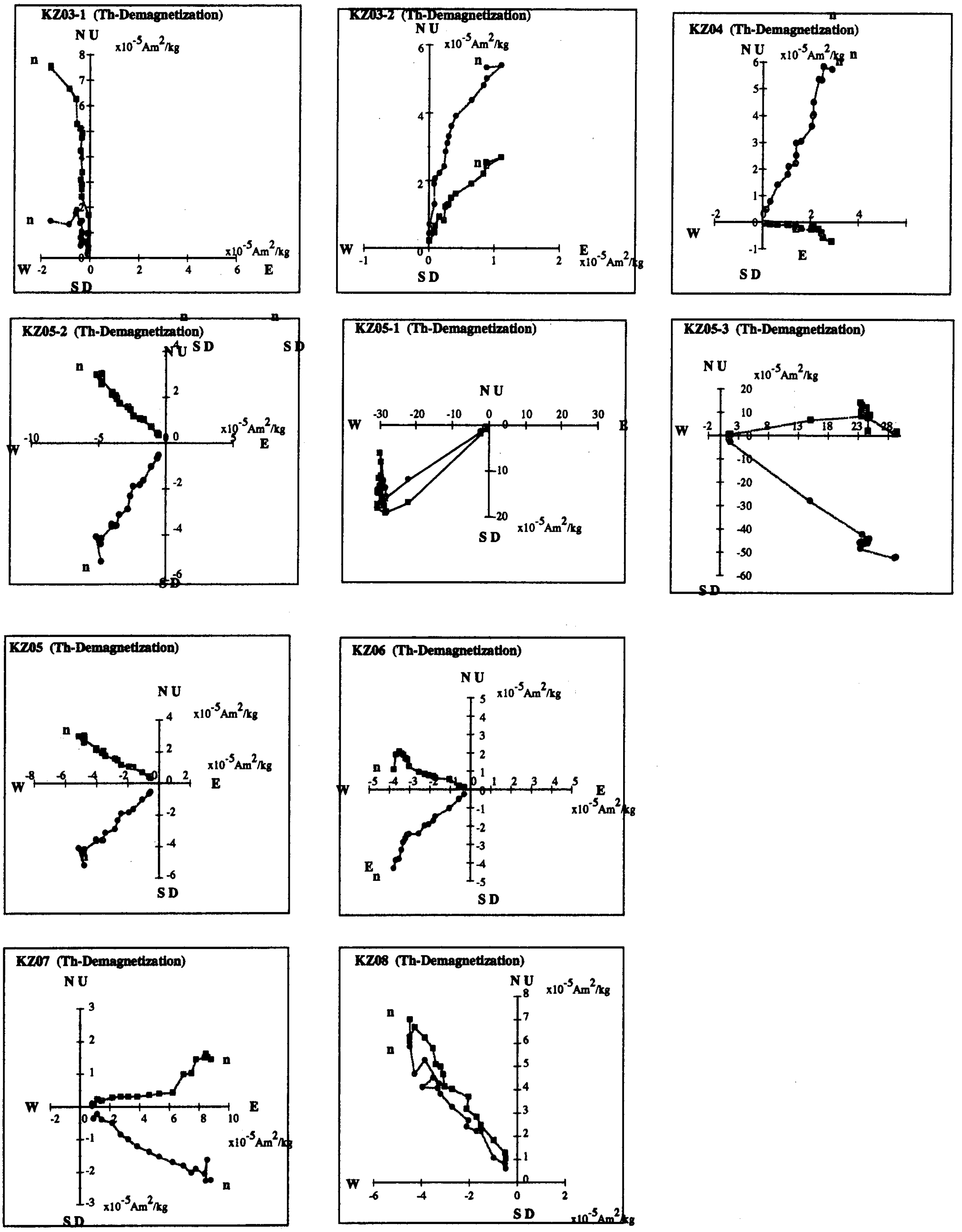


Fig.3—(3), Experimental results of ten baked silt samples obtained from peperite near the Senryoike Pond. Zijderveld projections of demagnetized ChRMs.

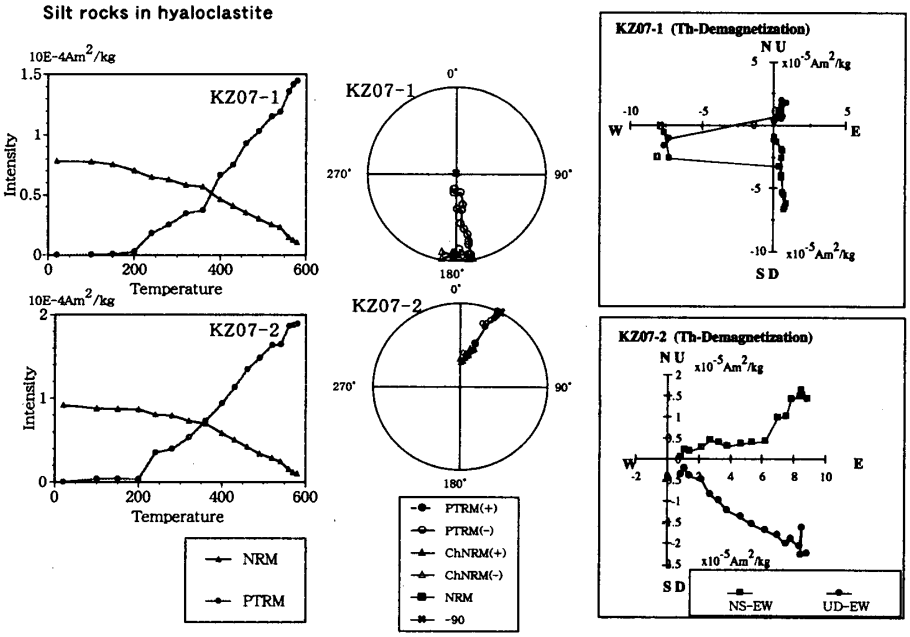
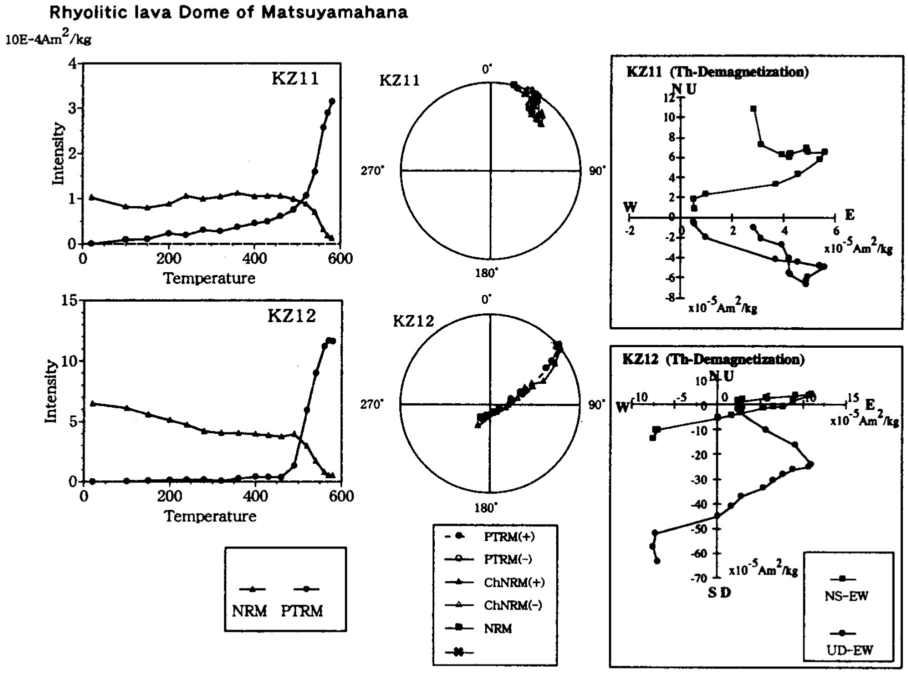


Fig.4 Experimental results of silt samples including rhyolite of "Lava flow of Membo volcano"near the Senryoike Pond.
Left figures are magnetic intensities of PTRMs and of ChRMs. Central figures are the direction changes of PTRMs and of ChRMs. Right figures are Zijderveld projections of demagnetized ChRMs.



Fingure.5 Experimental results of rhyolite samples obtained from "Lava dome of Matsuyamahana volcano" at the eastern margin of the Miura Bay.
Left figures are magnetic intensities of PTRMs and of ChRMs. Central figures are the direction changes of PTRMs and of ChRMs. Right figures are Zijderveld projections of demagnetized ChRMs.

6. Discussion

Stepwise thermal demagnetization is useful method to analyze thermal history of igneous rocks (Prévot, and Perrin, 1992 ; Fujisawa *et al.*, 2001 in Japanese) Almost papers published before studied thermal history only using stepwise thermal demagnetization. On the other hand, stepwise thermal remagnetization is useful method to analyze thermal remanent magnetic property of igneous rocks. Why do we have to check the thermal remanent magnetic property of Kozu-shima Island's volcanic rocks? It is the reason that volcanic rocks in Kozu-shima Island is rhyolite and that STRM (self-reversal thermal remanent magnetization) are found in rhyolite or in dacite (Schult, 1968 ; Ozima and Funaki, 2001 ; Ozima *et al.*, 1992 ; Yama-ai *et al.*, 1963 ; Ueno *et al.*, 2001 in Japanese). STRM is the property to magnetize in reversed direction of external field. Thus, STRM rocks cannot be used for paleomagnetic analysis. Stepwise PTRM test is the easiest method to find STRM rocks, because intensity and direction of remanent magnetization of STRM rock change marvelously at 200-300℃. On the other hand, TRM direction goes to the normal direction after heating to the Curie temperature and cooling in the external field. Therefore, we measured stepwise thermal demagnetization and stepwise PTRM remagnetization of samples. This method is the same as the Thellier method. With the result, samples obtained from Kozu-shima Island do not have STRM, and we decide to discuss their thermal history using paleomagnetism.

Almost all samples without KZ02 have blocking temperature of 580℃ which is almost the same of Curie temperature of the titanless magnetite. KZ02 obtained from "Lava flow of Menbo volcano", has low blocking temperature of 250-300℃. With reflective microscopic observation, the magnetic source element is confirmed a small magnetite. This small size magnetite is considered the origin of stable remanent magnetization.

From Zijderveld projections of "Lava flow of Membo volcano" and of silt rocks within peperite and within hyaloclastite of this lava, we have concluded that these deposited temperature was mainly above 580℃ which is Curie temperature. Additionally, this lava block has not moved largely below Curie temperature.

KZ01 sample was collected from hyaloclastite of "Lava flow of Membo volcano". This results show this sample moved at 400-430℃. Lava rock sample KZ02, which is not hyaloclastite, is collected near KZ01, but KZ02 did not move beneath the Curie temperature. Peperite samples in "Lava flow of Membo volcano" also settled beneath the Curie temperature. Therefore, it is estimated that "Lava flow of Membo volcano" flowed into the water and became hyaloclastite about at 400-430℃.

While "Lava dome of Matsuyamahana volcano" has moved at 460℃-490℃ below Curie temperature, which is clearly shown from Zijderveld projections of KZ11–12. Therefore, it is concluded that "Lava dome of Matsuyamahana volcano" has deposited once at 460℃–490℃.

An important problem for Kozu–shima Island's volcanic rocks is that ChRM directions differ from each others, and largely from the Geomagnetic North Pole. These results explain that these rocks have moved randomly after depositing and after cooling completely.

7. Conclusion remarks

From thermal paleomagnetic experiments, the magnetic properties and the thermal history of Kozu–shima Island volcanic rocks ; "Lava flow of Menbo volacano" and "Lava dome of Matsuyamahana volcano", are concluded as follows.

1) The source of NRM of studied rocks without KZ02 ("Lava flow of Menbo volcano"), is titanless magnetite which have blocking temperature of 580℃.
2) The studied samples have stable remanent magnetization.
3) "Lava flow of Menbo volacano" has deposited at high above 580℃, which is Curie temperature of magnetite.
4) Silt rocks within peperite and within hyaloclastite of "Lava Flow of Menbo volcano", have also deposited at high above 580℃.
5) Hyaloclastite in "Lava flow of Menbo volacano" flowed into water at 400–430℃.
6) "Lava dome of Matsuyamahana volcano" has moved at 460℃–490℃ below Curie temperature.
7) Studied rocks have moved randomly after depositing and after cooling completely.

8. Acknowledgements

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要　旨

神津島（北緯34.3°，東経139.2°）は伊豆小笠原弧に属する流紋岩質の火山島であり，更新世から完新世にわたる流紋岩質火山活動による溶岩・火砕岩からなっている。本研究に用いた試料は，第I期（流紋岩質火山活動初期）の，面房溶岩類の噴出にともなう，岩相の異なる火山噴出物である。また，比較対照として，第II期流紋岩質火山活動の松山鼻溶岩円頂丘活動による流紋岩質ハイアロクラスタイトの試料についても，実験をおこなった。

面房溶岩類は，神津島東南端の千両池付近の海岸で採取した。面房溶岩は白色および黒色のガラス脈をともなう流理構造の発達した塊状流紋岩である。試料を採取した千両池付近では，面房溶岩は，海水との接触により，水とマグマの相互作用による様々な産状を呈する。今回主要に採

取したのは，面房溶岩が高温の状態でシルト質の堆積物と混在しているペペライトの赤色シルト部分である。なお，10試料のうち2試料はシルトと溶岩が混在する接触部である。溶岩体から離れるとペペライトは同様の赤色のシルトは含むハイアロクラスタイトへと漸移する。このハイアロクラスタイト中の赤色シルトからも2試料のシルトを採取した。さらにハイアロクラスタイト状のガラス質溶岩部分と，溶岩流の流紋岩を，それぞれ1試料づつ採取した。さらに長崎地域海岸にて，松山鼻溶岩のハイアロクラスタイトに含まれている流紋岩質本質岩片2試料を採取した。

試料すべてについて，段階熱消磁と段階部分熱残留磁化（PTRM）付加を繰り返した。両者とも，100-200℃間は50℃おき，200-400℃間は40℃おき，400-520℃間は30℃おき，520-560℃間は50℃おき，さらに560-580℃間は10℃おきでおこなった。PTRMの直流磁場は50μTである。

面房溶岩類ペペライトの赤色のシルト試料は，10試料とも熱消磁による磁化強度変化およびPTRM付加カーブの結果が似ており，同じシルト岩を起源としており，また，安定した熱残留磁化を持っている。というのも，同試料の熱磁化強度変化曲線は1相であり，推定されるキュリー点は580℃近くであり，このことから磁性鉱物はTiの少ない磁鉄鉱1種類なのではないかと思われる。熱消磁における自然残留磁化（NRM）の磁化方位は，接触部の試料をのぞき580℃まで大きく変化しない。よって，これらのシルトは580℃以上の温度にいったん上昇してからそのまま冷却していると考えられる。つまり，ペペライトは580度より高温で堆積した可能性が高い。同じ面房溶岩の本体から得た試料は，580℃以下で大きく方向を変えて動いた形跡はない。また，面房溶岩のハイアロクラスタイト中の流紋岩溶岩片試料では，490-520℃とペペライトより低温の滅消磁段階で，NRM方位が変化している。水との反応で，急冷相が発達しているところから，この温度が水中に流れ込んだハイアロクラスタイトの堆積時の温度と推定できる。

さらに，比較試料である長崎地域の松山鼻火山の黒曜石質ハイアロクラスタイト中の流紋岩片は，冷却する間に何回か動いていると思われる。神津島の流紋岩質溶岩はマグマの粘性が大きいため，これらの試料の熱消磁の結果は，冷却時の動きが緩慢であることを示している。