SUBAQUEOUS PYROCLASTIC FLOW DEPOSITS IN THE UPPER DONZURUBO FORMATION, NIJO-SAN DISTRICT, OSAKA, JAPAN

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Introduction

From the observations of historic incandescent avalanche deposits, many geologists have agreed that all terrestrial pyroclastic flow deposits were originated in eruptions often called hot glowing avalanche or nuée ardente (LACROIX, 1930). Hitherto, the term pyroclastic flow deposits has generally been used for such high temperature terrestrial deposits (ARAMAKI, 1957). On the other hand, the term subaqueous pyroclastic flow is advocated by FISKE (1963) for underwater flow of freshly erupted pyroclastic debris.

From abundant literatures on the terrestrial ash-flow deposits, one can comprehend that ash-flow deposits have various temperatures up to the order of 1,000°C in their depositions (SMITH, 1960). While it is generally accepted that the subaqueous pyroclastic flow deposits should settle at low temperatures, because of the contamination with cold water (FISKE and MATSUDA, 1964). If a different flow mechanism without mixing with cold water is found, however, some subaqueous pyroclastic flow deposits can also settle, maintaining their initial high temperatures. The term subaqueous pyroclastic flow deposits used in this paper mean such high temperature ones.

Since the temperature condition of ash-flow deposit is one of the most important characters intimately related with the flow mechanism, the determination of its emplacement temperature requires careful considerations, including magnetic measurements.

In this paper, attention is focused only on the Upper Donzurubo Formation, a small part of the Nijo Group, well exposed in the Nijo-san district, Osaka, Japan. The majority of the Nijo Group

is composed of pyroclastic flow and fall deposits of late Miocene to early Pliocene, and some of them are regarded to have been deposited in fresh water environments. In this volcanic sequence we found some interesting pyroclastic flow deposits, which were settled in subaqueous conditions maintaining high temperatures.

General Remarks on the Nijo Group

MORIMOTO *et al.* (1953, 1957) summarized the history of Cenozoic volcanism in the Setouchi (Inland Sea) province which lies in the middle zone of the Southwestern Japan. The First Inland Sea (Dai'ichi Setonaikai) (IKEBE, 1956, 1957 and HUZITA, 1962), which was once extended by the marine invasion in the middle Miocene, was then changed by the regression to a range of fresh water lakes. In one of these lakes, the volcanic strata of Nijo Group were deposited, which were mainly composed of pyroclastic deposits supplied by the volcanic activity of the so-called Setouchi Volcanic Series. The outline of such volcanic activity in Nijo-san district is given by MORIMOTO *et al.* (1957) as follows:

The activity began with the effusions of rhyolites or pitchstones, which were followed by outflows of biotite andesites, hornblende andesites and pyroxene andesites and finished by the extrusions of aphanitic lavas of hypersthene andesites or dacites, generally called "Sanukites". All these rocks belong to the calc-alkaline rock series. The volcano-stratigraphic sequence of the Nijo Group was summarized by MORIMOTO *et al.* (1953) as shown in Table 1.

YAMAZAKI and ONUKI (1969) and KATO *et al.* (1969), however, suggested from the stratigraphic and petrographic view point that the volcanic activity in the Nijo-san district in the late Miocene to early Pliocene should be divided into the following two stages. The first is the stage of the volcanic eruptions in the Nijo-san area proper,

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Table 1. The stratigraphic relations between the sedimentary deposits and the volcanics of the Nijo Group. (Simplified from MORIMOTO *et al.* (1953))

Osaka Group	
Jogashiro Formation	
Tamateyama tuff	
	Terayama lavas (biotite dacite)
Nijo Group	Haragawa Formation
	Myojinyama lavas (hornblende-bearing hypersthene dacite)
	Kasugayama lavas ("sanukite" and aphanitic hypersthene andesite)
	Odake lavas (aphanitic hornblende bearing hypersthene dacite)
	Upper Donzurubo Formation
	Medake lavas (biotite dacite)
	Anamushi conglomerate
Nijo Group	Hata lavas (porphyritic hypersthene andesite)
	Middle Donzurubo Formation
	Ishikiriba lavas (garnet biotite andesite)
Nijo Group	Lower Donzurubo Formation
	Rokuya lavas (biotite pitchstone)
Basements (Gneisses, Granitic Rocks)	

and the second is that of the eruptions in the Terayama area which is situated in the northern part of the Nijo-san district.

The first stage of the volcanic activity began with the effusion of rhyolitic pyroclastic deposits corresponding to the so-called Lower Donzurubo Formation. The eruption column, however, is not intercalated with any hard lavas. The Rokuya lavas which have been regarded as pitchstones are found in fact to be rhyolitic pumice-flow deposits containing welded tuffs (KATO *et al.* unpublished data). This finding by the present authors was affirmed by Dr. K. YAGI of the Hokkaido University and Dr. T. MATSUMOTO of the Okayama University in the field.

After a short interval, this activity was followed by the deposition of the Middle Donzurubo Formation, which is intercalated by the outflows of biotite garnet andesite (Ishikiriba lavas*) as well as some pyroclastic flows. Then, a short calm stage went on before the deposition of the overlying rhyolitic pyroclastic deposits, namely the Upper Donzurubo Formation. The succeeding volcanic eruptions of Upper Donzurubo Formation will be discussed in detail in the next chapter.

According to the authors' investigations, the Anamushi Conglomerate is identified either as the basal facies of the Upper Donzurubo Formation or a member intercalated in the underlying Middle Donzurubo Formation and the Haragawa Formation is identified as the uppermost member of the Nijo Group proper. In other words, both

the Anamushi Conglomerate and the Haragawa Formation are the marginal facies progressively developed in the shifting zones of the sedimentation of the Nijo Group. They are actually char-

Fig. 1. Index map of Nijo-san district.

* The age of this lava measured by K-Ar dating method is 16×10^6 years (KAWANO and UEDA, 1964).

acterized by the granitic boulders embedded in arkosic sand which were supplied from the basement rocks.

The eruption of the second stage began with the outflow of the Terayama lavas overlying unconformably the abovementioned strata.

The volcanic sequence of this stage is composed of lavas, agglomerates and auto-brecciated lavas accompanied with a small amount of pyroclastic flow deposits and subaqueous ash-fall deposits. Non-pyroclastic sediments of this stage are also mainly due to marginal sedimentation in fresh water. The Jogashiro Formation, which is the characteristic conglomerate facies including large blocks and boulders of gabbroic rocks and other basement rocks, is one of these marginal sediments intercalated chiefly in the lower parts of the sequence. Similarly the Tamateyama Tuff was assigned by the authors as a member intercalated in the upper part of this sequence.

Though the old names may not be suitable for the terminology of stratigraphic subdivisions as just mentioned, they are used in this paper to avoid a confusion between the newly defined units and old ones.

The Upper Donzurubo Formation

The Upper Donzurubo Formation is distributed chiefly in the north to northwestern parts of the Nijo-san area underlain by the middle and lower horizons of the Nijo Group. With the north-northwestward dipping monoclinic structure as a whole, it extends to the Terayama area, con-

formably overlain by the Haragawa Formation and other strata settled during the second stage.

Its typical stratigraphic column may be observed at Donzurubo, well-known for its scenic beauty. Its fine view can be ascribed to the good exposures of well-bedded pyroclastics in monoclinic structure, forming a kind of cuesta. Throughout the sequence it is composed entirely of pyroclastic debris interbedded with no epiclastic sediments, except for being conformably underlain by the Anamushi Conglomerate and overlain by the Haragawa Formation. The greater parts of the pyroclastics are composed of coarse-grained massive vitric tuffs, lapilli-tuffs and tuff breccias, several meters in thickness, and the remainders are thinner beds of very fine laminated tuffs interbedded in the formers at various horizons of the column. The total thickness of these strata is about 150 m.

The essential materials in the above-mentioned tuffs are dark gray to black colored, dense, angular perlitic fragments of rhyolitic composition, ranging from 5 to 10 cm in diameter. Frequently the fragments are slightly vesiculated. With decrease in diameter they grade into the coarser fractions of the matrix, composed of finer vesiculated particles, ashy materials and some crystal fragments. Accidental fragments of granitic rocks or other basement rocks are rare, while the accessory blocks of the Hata lava, ranging from several to scores of centimeters in diameter, are very often concentrated in the middle to lower horizons of the stratigraphic column.

Although the massive tuffs are slightly graded

Fig. 2. A : Reverse zoning observed in a tuff bed interbedded in the Upper Donzurubo Formation.

B : Magnified view of the reverse zoning.

a : fine ash

b : vesiculated fragments of rhyolite

c : coarse grained graded ash

or nongraded, the upper part of each bed is mostly finer-grained. The fine tuffs, intercalated in the above-mentioned massive tuffs, are characterized by fine laminations and vertical grading in individual laminae, often being accompanied by the reverse zoning. It is observed by the reverse arrangements of the coarser fractions of vesiculated rhyolite glass in the upper finer part of the laminae, as shown in Fig. 2. Besides the above-mentioned sedimentary structures, ripples, slumpings, loadings and some other deformation structures are frequently observed. These stratigraphic evidences suggest strongly that these strata were settled rapidly in subaqueous environments.

The subaqueous pyroclastic flow deposits in question occur as members of such subaqueous pyroclastic strata, which crop out on the new cut of the quarry along the upper stream of the Hara river, about 4 km northwest of Mt. Nijo (Figs. 1

and 3). The sequence corresponds to the uppermost part of the above-mentioned monoclinic column of the Upper Donzurubo Formation. It is successively overlain by the Haragawa Formation at the top of the outcrop, and just on the opposite side of the Hara river it is unconformably underlain by the Terayama lava (Fig. 3).

The strata consist entirely of fragmental debris of rhyolite glass without any intercalations of epiclastic sediments. Neither accessory fragments of the Hata lava nor accidental fragments of the basement rocks are found in these strata, though they are frequently found in the main part of the Upper Donzurubo Formation underlying this sequence. The feature of this outcrop is schematically shown in Fig. 4. On the basis of the stratigraphic relation and the lithologic features, the pyroclastic sequence was subdivided into ten units, namely units A~J in ascending order. They

Fig. 3. Geologic map of study area.

A~J : stratigraphic units (see Fig. 4)

Hg : Haragawa Formation

Fig. 4. Profile showing the stratigraphic relations between the subaqueous hot avalanche deposits (units A, B, C and E) and other subaqueous pyroclastic deposits (ash-fall tuffs, units D and F; explosion breccias, unit H; mud flows, units G, I and J).

occur in four main facies as follows.

- (a) The units A, B, C and E form massive beds of fragmental debris ranging in thickness from 0 to about 4.5 m.
- (b) The units D and F form much thinner beds of laminated tuff ranging in thickness from 0 to 1.5 m.
- (c) The units G, I and J form massive beds ranging in thickness from 0 to about 4 m.
- (d) The unit H forms massive boulder beds intercalated by cross-laminated tuff ranging in thickness from 0 to about 3.5 m.

The detailed features of these main facies are described below.

(a) Units A, B, C and E

These units have some characteristic features of pyroclastic flow deposits as shown below. All units are massive and nongraded, and sometimes show erosive action against the underlying stratum. Though rather structureless, their basal parts are finer-grained and often characterized by a kind of cross-laminations. They are composed of broken pieces of essential materials. It is conspicuous in the units C and E that the uppermost parts, about 30 cm in thickness, are finer-grained. Vesiculated blocks of essential materials are sporadically embedded in these uppermost parts. Larger essential fragments are usually accumulated in the middle part of each unit, as it is marked in the unit E (Fig. 5).

These units carry no accidental nor accessory blocks. The essential fragments are quite the same in lithology as those in other horizons of the Upper Donzurubo Formation. They are dark gray to black colored, dense, non-vesiculated glassy rhyolites. Their petrographic descriptions are given in the next chapter. The essential fragments are scattered with no relation to their shapes and orientations of flow structures. The finer particles and the matrix of these units are composed of the same materials as large essential fragments.

(b) Units D and F

The units D and F are thin-bedded and cross-laminated tuffs, which are considered to be originated from ash-fall deposits. The coarser particles are composed of pale gray to yellowish white, slightly vesiculated angular pieces of rhyolite glass. They grade progressively into finer sand-sized particles in individual laminae. Dark gray to black colored perlitic lapilli-sized fragments are sporadically embedded, which have the same lithologic features as the essential materials in other units. The sequence has always sharp boundary with the underlying massive bed, while the upper boundary is frequently scoured by the overlying

Fig. 5. Outcrop of the stratigraphic units C~F.

a : vesiculated fragments of rhyolite sporadically embedded in the uppermost part of the unit C.

b : non-vesiculated angular fragments of rhyolite accumulated in the middle part of the unit E.

D, F : laminated tuffs originated from ash-fall deposits.

massive bed. Thus the units thin out or wash out completely as shown in the profiles (Figs. 4 and 5). Some reverse zonings and also load casts are often developed in the unit F by the load of the overlying massive bed G.

(c) Units G, I and J

The unit G has a rather similar aspect to the massive tuff beds constituting the greater part of the Upper Donzurubo Formation. It is composed entirely of pyroclastic debris of essential rhyolite glass, being a little finer than the underlying massive beds, A, B, C and E. The basal part of the unit, however, is more or less graded and cross-bedded, and often carries load casts on the underlying bed F. Its uppermost part is generally composed of ashy matrix, in which essential blocks of glassy rhyolite are sporadically embedded.

Units I and J are scarcely graded, but are composed of roughly bedded boulder beds. A large quantity of angular essential rhyolite boulders,

from several to scores of centimeters in diameter, are embedded in the matrix of vesiculated lapilli and ashy materials. A large scale scouring is observed at the base of the uppermost unit J, which overlies directly the units G and H (Fig. 4). These structural features and their magnetic data suggest that they were originated from some mud flows.

(d) Unit H

The sequence of this unit is composed of alternation of essential boulder beds and fine cross-laminated tuffs. The uneven surfaces of the roughly accumulated essential boulders are covered by fine-laminated tuffs, and moreover the spaces of the individual boulders are filled with fine tuffs. It seems, therefore, not suitable to use the term alternation in strict sense for this unit. The cross-laminated tuffs are often caved in by the load of essential boulders. It seems that this unit was originated from explosion breccias.

Description of Essential Materials in the Pyroclastic Flow Deposits

The essential materials of the pyroclastic flow deposits are the same as those of the overlying and underlying explosion breccias, mud flows and ash-fall deposits. They are garnet-bearing biotite rhyolite of calc-alkaline rock series.

Megascopically, the essential materials are black, glassy, angular fragments, 5 to 10 cm in diameter. They carry sporadically small phenocrysts (about 0.5 mm in diameter) of plagioclase, biotite and garnet. In the upper part of the flow unit C, vesiculated fragments are sporadically embedded in fine ashy matrix. Fine perlitic cracks are characteristically developed in all essential fragments, especially in those from the lower part of each cooling unit. Flow structures are also observed, but they have no relation with the shape or orientation of essential materials.

Plagioclase ($An\ 42\sim39$, $\alpha\ min.=1.548\pm0.001$, $\gamma\ max.=1.558\pm0.001$), biotite ($\beta=1.652\pm0.001$) and garnet ($n_0=1.815\pm0.005$) are present rarely as phenocrysts. Garnet in this rock is considered to be almandine-rich variety from the optical similarity to the phenocrystic garnet in the Ishikiriba lava (YAMAZAKI, 1958). Quartz or alkali feldspar is not observed as phenocryst. The groundmass is mainly composed of glass ($n_0=1.507\pm0.001$), carrying fine lath-shaped plagioclase, biotite and magnetite (smaller than 0.01 mm). The crystallinity of groundmass is varied with the structural position of the rock fragment in each flow unit. In the lower and uppermost parts of each flow unit, the groundmass of essential block is mainly

Table 2. Chemical and normative composition of groundmass of garnet-bearing biotite rhyolite, the essential fragment from the subaqueous pyroclastic flow deposit (unit B). (after YAMAZAKI and ONUKI, 1969)

SiO ₂	71.70	q	32.67
TiO ₂	0.09	c	1.59
Al ₂ O ₃	13.88	or	20.71
Fe ₂ O ₃	0.76	ab	31.89
FeO	1.31	an	6.34
MnO	0.07	wo	—
MgO	0.18	en	0.45
CaO	1.32	fs	1.74
Na ₂ O	3.75	mt	1.11
K ₂ O	3.50	hm	—
H ₂ O ⁺	2.86	il	0.17
H ₂ O ⁻	0.24	ap	0.07
P ₂ O ₅	0.03		
Total	99.69		

Anal. H. ONUKI

composed of glass, but in the central part it carries more abundant crystals.

Chemical composition of the groundmass is given in Table 2. It shows a typical rhyolitic composition of Mg-poor group of calc-alkaline rock series in Nijo-san district (YAMAZAKI and ONUKI, 1969).

Density of an essential fragment is 2.423 g/cm³ at 25°C.

Magnetic Measurements

1) A new apparatus for measurements of NRM

The natural remnant magnetization was measured by an astatic magnetometer (1×10^{-7} oe/mm) with an automatically recording system instead of an ordinary lamp-scale reading method (MURŌI, 1969).

In this apparatus two solar cells, connected differentially in their electric polarity to detect the same deviation, were employed. Out put voltage from the cells was amplified and recorded automatically.

The specimen on the sample stage was rotated by a belt which is driven by a synchronous motor at a distance of 2 m from the stage. The magnetization of each specimen, which is cut in cubic form ($2.5\times2.5\times2.5$ cm³), was observed in three orthogonal components. It takes 5 minutes to measure the NRM about one axis of the cube, and therefore 30 minutes are required for the complete observation of a specimen.

In order to detect the rotation angle of the stage, twelve mirrors, 10 mm in diameter, were fixed around the stage with an interval of 30°, and a source of light and a CdS photocell are

Fig. 6. Directions and mean intensities of NRM and average bulk densities of about 150 specimens from each stratigraphic units, A~J.

set up at a distance of 2 m from the stage. The CdS is connected to a relay which drives a marker pen. By rotating the stage, each mirror passes through a rest position, and the reflected light from the mirror arrives at the CdS. A pulse pattern showing the angle of 30° is traced by the pen on one side of the chart.

The direction and intensity of the magnetization were calculated with Fourier analysis method.

2) Natural remnant magnetization

About 150 specimens were collected from the units A to J for the measurement of NRM. The specimens from the units, A, B, C and E are the essential fragments in the pyroclastic flow deposits and those from the units, D and F are the matrix of the fall deposits. From the units, G, H, I and J also, the essential fragments were collected. The result are shown in Fig. 6. In this figure, the declination and inclination of each specimen, mean intensities of NRM and mean specific gravities for each unit are illustrated.

It is noticed in Fig. 6 that the magnetic directions of the essential fragments and the fall deposits from A to F are in good coincidence, while those of the essential fragments from G to J show random scattering. The relation between the intensities and the stratigraphic units is discussed later.

3) Alternating field demagnetization

The stability tests were carried out by alternating field demagnetization technique by means of the apparatus which is nearly the same as usually used. The specimen of cubic size with 2.5 cm edge was tumbled around three orthogonal axes within an alternating field produced by a pair of emerging coil of Helmholtz' configuration with a maximum field of 720 oersteds r.m.s.

In this study field strength up to 600 oersteds r.m.s. was applied. The magnetic cleaning was performed at the center of field-free space compensated by three pairs of circular Helmholtz' coil which is set perpendicular to each other to cancel the earth's magnetic field. The remnant magnetization before and after the demagnetization was measured by the astatic magnetometer mentioned above.

Five specimens were selected for the stability test. Two of these specimens, J-1 and BM-16, are both essential fragments embedded in units J and B respectively. The remaining three specimens, F-4, D-3 and CU-1 are pyroclastic debris, collected respectively from the bedded tuffs of the units F and D, and the matrix of the uppermost part of the unit C.

These specimens were subjected to the alterna-

Fig. 7. Alternating field demagnetization curves.

J-1, BM-16 : essential fragments from the units J and B

CU-1 : matrix of the upper part of the unit C

F-4, D-3 : the ash-fall deposits of the units F and D

ting fields with progressively higher r. m. s. values of 100, 200, 300, 400, 500 and 600 oersteds, in addition to 70 and 140 oersteds applied for the first two specimens. The decreasing curves of the magnetization to the applied field up to 500 or 600 oersteds are shown in Fig. 7, and the resulting direction changes of the remnant magnetization after alternating field demagnetization are plotted in the lower hemisphere of a stereographic projection (Fig. 8).

As evident in the figures, those curves of J-1,

Fig. 8. Stereographic projection of the direction changes due to alternating field demagnetization (plotted in lower hemisphere).

+ : mean direction (from A~F)

The other symbols are the same as in Fig. 7.

B_M -16 and C_U -1 are similar, though the value J/J_0 of J-1 decreases by about 30%, and the magnetic direction of these three specimens are not appreciably changed. On the contrary, the value of D-3 decreases very rapidly about 90% for the ac field up to 500 oersteds and the change of magnetic direction is markedly larger than that of the above-described specimens. It must be noticed, however, that the direction approaches to the mean value of the direction of the units A~F. The specimen F-4 shows a similar behavior to D-3.

4) Thermal change and Curie point

The thermal change of saturation magnetization and the Curie point of the specimens were measured with a magnetic balance.

The saturation magnetization (J_s)-temperature (T) curves for 10 specimens were obtained by the magnetic balance at temperatures ranging from

room temperature to 600°C or more in both heating and cooling processes in air. Four examples are shown in Fig. 9, a~d, in which the ordinate gives the ratio of $J_s(T)/J_s(T_0)$, and the abscissa gives temperature T . These curves change slightly irreversibly with temperature in heating and cooling cycles. This may be due to the heat treatment in air. The observed Curie points are within the temperature from 540°C to 580°C, meaning the existence of magnetite as a chief magnetic mineral in the specimens.

The differences of the J_s - T curves in heating and cooling processes are seen within the temperature range from 50°C to 450°C. It is especially interesting that the differences in the units D and D (Fig. 9, c~d) are larger than those of the units A and E (Fig. 9, a~b). In spite of these differences, the saturation magnetization at the initial room temperature became nearly equal

Fig. 9. a : J_s - T curve for the essential fragment A_L -6 from the unit A (Hex=9,800 gauss)
 b : J_s - T curve for the essential fragment E-6 from the unit E (Hex=10,200 gauss)
 c : J_s - T curve for the ash-fall deposit D-3 from the unit D (Hex=11,200 gauss)
 d : J_s - T curve for the ash-fall deposit F-4 from the unit F (Hex=11,100 gauss)

except that of the unit A.

5) Thermal demagnetization

In order to examine more precisely the J_s - T and the magnetic properties, thermal demagnetization was carried out by an electric furnace in a non-magnetic space made by an shield case of Mu-metal (a kind of alloys with high permeability) and three pairs of square coils.

The thermal demagnetization curves are shown

Fig. 10. a : Curve of thermal demagnetization of NRM for the essential fragment E-5 from the unit E.

b : Curve of thermal demagnetization of NRM for the ash-fall deposit F-4 from the unit F.

Fig. 11. Stereographic projection of the change of NRM directions due to thermal treatment in the essential fragment E-5 from the unit E.

R. T. : room temperature

Figures give the heating temperature in °C.

in Fig. 10, a~b. The former is a curve of an essential fragment from the unit E, and the latter is a curve for the tuff from the unit F.

The Curie point of the essential fragment is about 570°C as observed in Fig. 10 a more clearly than in the J_s - T curve of Fig. 9 b. The variation of the magnetic direction in heating is shown in Fig. 11. As shown in Fig. 10 b, the NRM of the fall deposit at 360°C decreases to one-fifth of the initial intensity, and above 360°C the remaining NRM decreases gradually until about 570°C and becomes zero at 725°C. The detailed investigations of the thermal demagnetization and thermo-remnant magnetization for each unit are still going on.

Discussion

1) Natural remnant magnetization

(a) *NRM of the essential fragments from the units A, B, C and E.*

Judging from the above-mentioned results, it is evident that the NRM of the essential fragments is due to magnetite, and consists almost only of TRM (thermo-remnant magnetization) acquired without chemical reactions in the cooling stage of their emplacement. The NRM was found also to be very stable from the results of the ac- and thermal demagnetization.

(b) *NRM of the tuffs originated from ash-fall deposits F and D.*

From the facts that (1) the strength of the NRM is weak, (2) the stability is more or less low and (3) three Curie points are found on the thermal demagnetization curve (Fig. 10 b), the NRM of the tuffs was proved to be different from that of the essential fragments.

As shown in Fig. 10 b, it seems likely that the greater part of the NRM below 360°C was acquired by maghemite (determined under reflective microscope), and the remaining NRM by the existence of two magnetic minerals, magnetite and hematite. In such case, the remnance is usually considered to be CRM (chemical remnant magnetization) as suggested by ARAMAKI and KAWAI (personal communication). It is generally accepted that the CRM is produced by the post-depositional chemical reactions of magnetic minerals.

On the other hand, NRM of sedimentary deposits are considered as both CRM and DRM (depositional or detritus remnant magnetization) (NAGATA, 1961). YUKUTAKE, NAKAMURA and HORAI (1964), in their investigation on the magnetization of the ash-fall tuffs of Oshima Volcano, strongly suggested that the tuffs have stable magnetization which was considered to be CRM and DRM,

although the mechanism of magnetization of the ash-fall tuffs remained unknown.

In the present observations, the authors noticed three kinds of NRM as follows.

The first is the DRM after the CRM of maghemite* produced by oxidation of finer grains of magnetite during the settling of the finer fractions of the ash-fall deposits.

The second is the DRM of magnetite enclosed in more or less larger particles of glassy fragments, which were settled without chemical reactions.

The third is the CRM of the hematite and maghemite produced by the chemical reactions after deposition, namely, by diagenetic alteration. Consequently the remnance of the units D and F is considered to be composed of such DRM and CRM.

2) Temperature estimations

Estimation of the temperatures of the pyroclastic deposits is very important in discussing the mechanism of their emplacement.

Several workers have reported on estimating the temperature of the pyroclastic deposits by means of the NRM directions, and have successfully discussed the mode of emplacements of those deposits (ARAMAKI, 1956; ARAMAKI and AKIMOTO, 1957; SUZUKI, 1962).

In the present study, the authors carried out the measurements of the stability by the ac dema-

gnetization, and the determination of the Curie points by the J_s -T and the thermal demagnetization as well as the directions of NRM.

As shown in Fig. 6, the lower part of the column (units A~F) is clearly distinguished from the upper part (units G~J) by the NRM directions, i. e., the former has a uniform orientation, whereas the latter random orientations. The results are sufficiently reliable because of the abovementioned stability tests. There is no need of apprehension that the uniform orientation of the NRM of the essential fragments was made by chance.

On the other hand, the Curie points of the specimens from the units A~F are within the range 540°C to 580°C as shown in Table 3. The J_s -T curve are more or less irreversible, and the degree of irreversibility is larger on the curves of the tuffs (D and F) than those of the essential fragments in the flow deposits (A, B, C and E).

The thermal history of the magnetic direction shows that the directions scarcely change up to 473°C and then move downward at 575°C in the stereographic projection (Fig. 11). It is estimated that the essential fragments had settled at the temperature range from 473°C to 575°C.

3) Mode of emplacement

Stratigraphic succession of the pyroclastic flow deposits in question is reconstructed in Table 3

Table 3. Stratigraphic units and palaeomagnetic data.

Stratigraphic sequence U : Upper M : Middle L : Lower	Thick- ness (m)	Measured materials	Magnetic mean values				Curie point Tc (°C)	Remarks		
			Numbers of samples	D	I	α	Intensity J(emu/cc)	Flow units	Cool- ing units	Eruption columns
F	0.8±	tuff (matrix)	3	356	40	19	2.84×10^{-5}	550		
E	2.0±	essential fragments	15	353	27	7	9.44	550	(4)	3
D	1.5±	tuff (matrix)	6	330	43	17	0.728	560		
C	3.5±	matrix	4	346	39	30	1.67	540	(3)	
		essential fragments	12	346	18	6	5.76	560		
B	4.5±	matrix	4	357	20	10	5.99	560	(2)	2
		essential fragments	32	350	34	4	12.1	580		
		//	4	346	9	12	4.62	580		
A	2.0±	essential fragments	3	355	14	15	4.62		(1)	1
		//	8	351	25	6	6.94	550		

D, I and α represent declination, inclination and Fisher's 95% circle of confidence in degrees, respectively.

* Further examinations are required for the mineralogy and the determination of Curie temperature of maghemite.

with their magnetic properties. The units A, B, C and E are nonsorted pyroclastic flow deposits resembling nuée ardente deposits (LACROIX, 1930). The units D and F are cross-laminated thin beds, composed almost of coarse ash- and lapilli-size fragments of essential materials which are lithologically the same as in the underlying pyroclastic flow deposits.

As mentioned before magnetic investigations show that the essential fragment in the unit E settled at high temperature, probably between 473°C and 575°C. Consequently it is natural to conclude that the pyroclastic flow deposits A, B, C and E can be considered as hot avalanches which flowed at least at temperatures higher than the Curie temperature of magnetite.

Some subaqueous volcanoclastic deposits (FISHER, 1966) in Sendai district were studied by SHIBATA (1962) from structural view point and were named by him as pyroclastic rubble deposits. FISKE (1963) and FISKE and MATSUDA (1964), in their studies on some subaqueous volcanoclastic deposits, concluded that hot ash-flows have never been produced in any subaqueous volcanic eruptions, because most of the ash was mingled with cold water and quenched before it could settle on the sea floor. However no magnetic properties of these deposits were given by them for determining the emplacement temperatures.

In subaqueous environments, it is very controversial whether or not a pyroclastic flow can move in the same mechanism as a terrestrial pyroclastic flow. YAGI *et al.* (1960) discussed the origin of welded tuff from density measurement of pumice from pumice-flow deposits of Towada caldera, and concluded that the bulk density of pumice flows is generally less than 1.0, thereby making it difficult for the pumice flows to accumulate firmly on the bottom of the sea, if they are erupted by submarine volcanic activity. SHIBATA (1962) demonstrated, however, some pyroclastic flow deposits settled *en masse* in subaqueous environments, though, he has not made any suggestion on the flowing and emplacement mechanism of his pyroclastic rubble flow. FISKE and MATSUDA (1964) stated that as dense fragments were settled back to the sea floor, they gradually formed a dense mush of quenched lapilli, ash and sea water, which became even denser as more debris continuously rained down and soon this mush became so overloaded that it flowed laterally and glided into the deeper parts of the basin as a subaqueous pyroclastic flow. But this flow should have easily distinguished from the primary pyroclastic flow, because this should have very low temperature

and moreover its behavior is considered essentially as a secondary dense flow deposit.

As shown before, the structural characters of the units A, B, C and E suggest that each unit was emplaced *en masse*. Although bulk density of the flowing mass cannot directly be estimated, the eroding evidences of the flowing mass strongly indicate that these pyroclastic flows could have moved as density flows even in subaqueous conditions. Bulk density of the essential fragments of these pyroclastic flow deposits is more than 2.0.

Conclusion

Mechanism of the subaqueous pyroclastic flows

From the magnetic measurements and the structural similarities to the terrestrial nuée ardente deposits, the authors consider that the subaqueous pyroclastic flow deposits in question were originated by the descending growing clouds (RITTMAN, 1960) due to the lateral explosion at the base of a lava dome. Moreover, some evidences provided by the essential fragments, namely (1) they are not vesiculated, (2) they have always irregular shapes, and (3) they carry well-developed flow structures, which have no relation with their external forms, support such descending growing cloud origin. It is natural to consider that the flowing temperatures of these descending growing clouds should have been higher than the emplacement temperatures of the essential fragments. Such high temperature estimations deny the mingling of the pyroclastic flows with cold water, nevertheless they rushed into cold water, several tens of meters in depth. For the formation of such subaqueous hot avalanche deposits, the depth of the water of the same order as the thickness of a single sheet corresponding to one eruption may be sufficient. From the stratigraphic data, however, the authors estimate that the depth of the water should have been about 50 m for these subaqueous pyroclastic flow deposits. The 1902 eruption of Mt. Pelée have produced such subaqueous pyroclastic flows (LACROIX, 1904).

The subaqueous conditions of the settlement of the deposits are not incompatible with the structural column. They can account for the existence of the lower chilled zone and fine grained uppermost zone in each cooling unit. It is noticed in Fig. 6 that magnetic intensity and bulk density of the essential blocks change systematically with the structural height in one cooling unit. This systematic change is also reflected in the change of crystallinity in the groundmass and of porosity of essential materials. As discussed in previous

chapters, the lower zone (B_L in Table 3) of structural unit B represents petrographically a chilled base of a cooling unit. Essential blocks in this zone carry abundant glass in its groundmass with well developed perlitic cracks. In central zone of the same cooling unit, microcrystalline materials are increased in groundmass of essential fragments and perlitic cracks are not so developed. No vesiculated essential fragments are observed in the lower or central zone, but some essential fragments carrying unconnected bubbles in limited extent are found in the uppermost zone. The microcrystalline materials in groundmass decrease gradually with the increasing structural height within one cooling unit. These petrographic evidences as well as their structural and magnetic properties suggest that the units B and C were settled successively *en masse* as hot avalanche deposits.

As SMITH (1960) stated in his excellent review on ash-flows, all observers of the nuée ardente phenomenon agree that the nuée ardente has two parts..... a basal avalanche and an overriding spectacularly expanding cloud of gas and dust. Therefore it is expected that any pyroclastic deposits of one volcanic eruption carrying a nuée ardente consist of lower dense part (pyroclastic flow deposits) and stratified upper fine part (ash-fall deposits). For example, the units B and C in Table 3 show the dense avalanche deposits and the overlying unit D is the tuff originated from ash-fall deposit of the same volcanic eruption. The distinction between the units B and C are due to the lamina flow within a hot avalanche (SMITH, 1960).

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二上山地域における上部ドンズルボー層中の水中火砕流堆積物

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(要 旨)

二上層群“上部ドンズルボー層”の上部に水中火砕流堆積物と考えられるものが、田尻峠と穴虫峠の中間の原川沿いに見いだされた。

本質火山岩片はザクロ石含有クロウンモ流紋岩で、全く発泡していない。マトリックスはそれと同質の細かい破砕片からなっている。この火砕流堆積物層および、これと一連の火山噴出物である降下火山灰や爆裂火砕岩、火山性泥流源の堆積層について詳しい岩石磁氣的検討を行なった。火砕流堆積物層の本質火山岩片とマトリックスは安定なジテッ鉱の TRM を保持し、さらにキュリー温度、熱消磁による帯磁方位の変化の測定結果から、この火砕流堆積物層が水中でありながら少なくともジテッ鉱のキュリー温度以上の高温で定着堆積したものであることを明らかにした。このような高温の水中火砕流堆積物層の形成機構については、Mt. Pelée の 1902 年の噴火にみられるような (Lacroix, A. 1904), 火山岩尖の中腹からの噴出による、比較的小規模な熱雲流が、数 10 m 前後の深さの水中に流れこんだものと推定した。また、このような形成機構にもとづき flow unit, cooling unit,

eruption column を区別することができた。これらの結果から水中の火砕流堆積物層においても、その定着堆積当時の温度推定が重要であり、陸上におけると同様、水中においても高温の火砕流堆積物層と低温の火山性泥流堆積物層とは区別せねばならないことを指摘した。

地	名
Anamushi Conglomerate	穴虫礫岩
Donzurubo (Formation)	屯鶴峯 (層)
Haragawa Formation	原川層
Hara river	原川
Hata lava	畑溶岩
Ishikiriba lava	石切場溶岩
Jogashiro Formation	定が城層
Nijo-san	二上山
Rokuya lava	鹿谷溶岩
Terayama	寺山
Yamato River	大和川