MODE OF ERUPTION AND DEPOSITION OF THE HACHINOHE PHREATOPLINIAN ASH FROM THE TOWADA VOLCANO, JAPAN

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Abstract The Hachinohe ash ($SiO_2 = 69$ %) is a 16 km^3 phreatoplinian fallout deposit erupted from the Towada volcano 13,000 years ago. It is composed of alternating beds of fine ash and pumice lapilli. Fine ash beds are made up of closely packed accretionary lapilli with open matrix. A number of accretionary lapilli are also found in pumice beds. The dynamic contact between erupting magma and lake water was responsible for the phreatomagmatic character of this deposit. In the course of the eruption, discharge rate of magma occasionally rose so that mass ratio of water to magma became lower than the ratio of an explosive maximum, when the style converted into a relatively magmatic eruption. Pumice beds indicate timing of these occurrences. The premature fallout of fine ash from eruption clouds in the form of accretionary lapilli or particle aggregates will be an inevitable process operating in phreatomagmatic eruption clouds. In the case of the Hachinohe eruption, it is supposed from spherical shapes of accretionary lapilli that they were frozen up during the descent before reaching the ground.

Key words: explosive eruption, magma-water interaction, accretionary lapilli, Towada volcano

1. Introduction

The Hachinohe ash of 13,000 years B.P. is the largest in volume among fallout deposits erupted from the Towada volcano (Hayakawa, 1983, 1985). It is rhyodacitic with 69 % of SiO_2. Along the dispersal axis, the thickness is 150 cm 50 km E of the source. The 100-cm isopach encloses more than 1,000 km^2 of land area (Fig. 1). Volume and mass of the deposit are estimated to be 16 km^3 and 1.1×10^{13}kg (Hayakawa, 1985). Photographs of a typical outcrop are shown in Fig. 2.

The ash is composed of alternating beds of fine ash and pumice lapilli. No erosional break is detected and contacts betweeen beds are gradational. It is directly overlain by a non-welded ignimbrite. Oike and Nakagawa (1979) divided the ash into six beds: HP1 ash, HP2 pumice, HP3 ash, HP4 pumice, HP5 ash, and HP6 pumice, in the stratigraphically ascending order. Figure 3 illustrates a series of columnar sections along the dispersal axis. There is no difficulty in identifying each bed in the field. The isopach

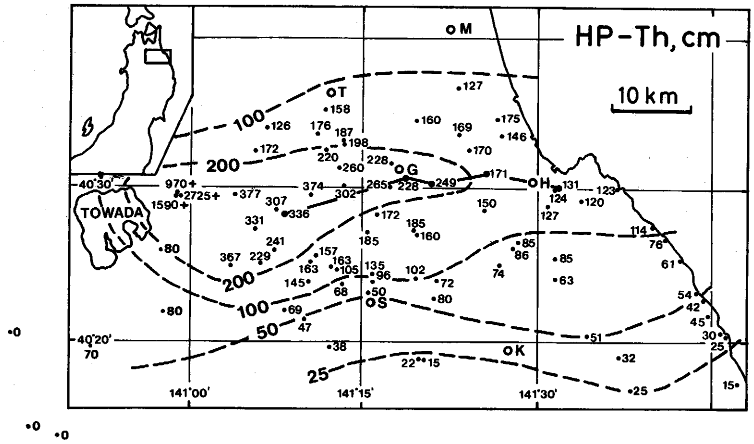


Fig. 1 Isopach map of the Hachinohe phreatoplinian ash (HP, Hayakawa, 1983; partly modified)
Values are in cm. Solid tieline indicates localities of sections in Fig. 3. M: Misawa; T: Towada; G: Gonohe; H: Hachinohe; S: San'nohe; K: Karumai

maps of all the six beds are shown in Fig. 4. Measured thicknesses except those for the HP6 pumice are highly reliable because they have been protected by immediate deposition of the succeeding unit. Surface of the HP6 pumice has been more or less eroded by pyroclastic flows.

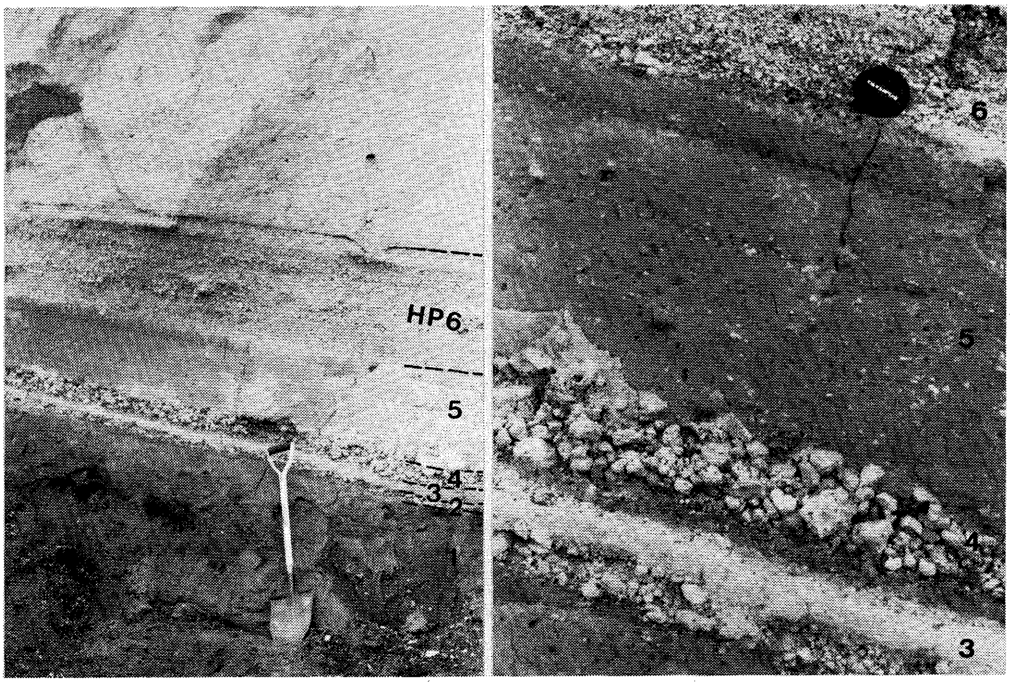
The rate of outward thinning of the ash is somewhat lower than those for plinian deposits of the same volcano (Hayakawa, 1985). The isopachs are nearly parallel or tongue-like in shape which are apparently different from an ellipse of common plinian deposits.

2. Field Characteristics

Ash beds

On the superficial examination the HP1, HP3, and HP5 ash beds seem to be massive. However, a closer study reveals a distinct sedimentary structure represented by closely packed accretionary lapilli with open matrix (Fig. 5). Accretionary lapilli are pellets of volcanic ash that commonly exhibit concentric structure (Moore and Peck, 1962). The majority of the Hachinohe lapilli is 2 to 8 mm in diameter. Some lapilli contain small pumice fragments in the core and others are wholly made up of massive vitric ash without core pumice. The maximum diameters of accretionary lapilli (MAL) are measured (Fig. 6). As far as 50 km from the source, there is no simple relation between the maximum size and distance from the source.

A small but not neglegible amount of fairly large, ash-coated, pumice fragments are enclosed in ash beds. The size is as large as those in pumice beds, about 5 cm in diameter 30 km away from the source.



(a) (b)

Fig. 2 (a) The Hachinohe phreatoplinian ash overlain by the Hachinohe ignimbrite, at Ken'yoshi, 36 km E of the source. The base of the ash is at the top of spade (80 cm long). (b) Close-up of a part of (a).

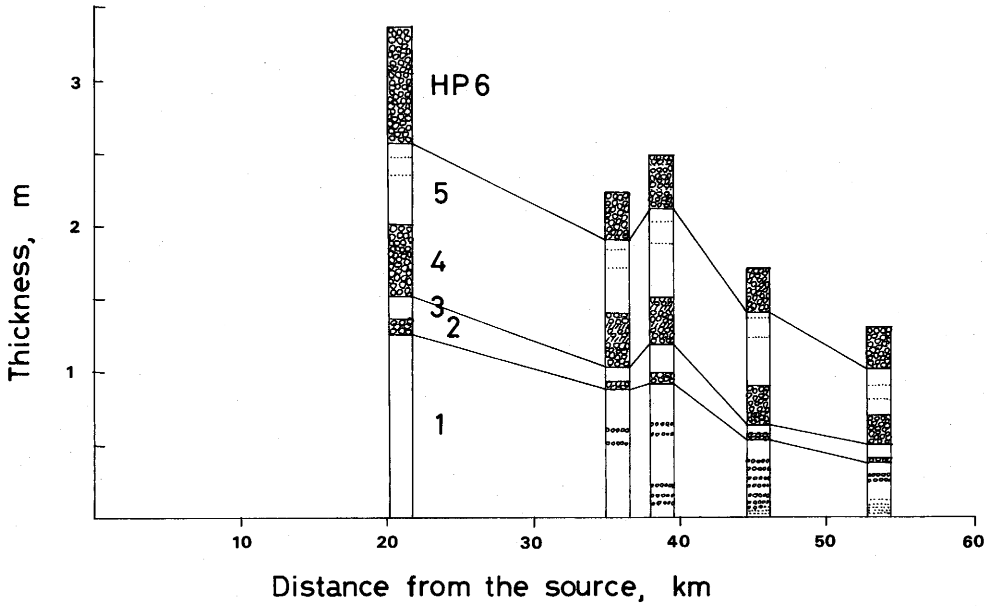


Fig. 3 A series of columnar sections of the Hachinohe ash along the dispersal axis Localities of sections are shown in Fig. 1 by a tieline.

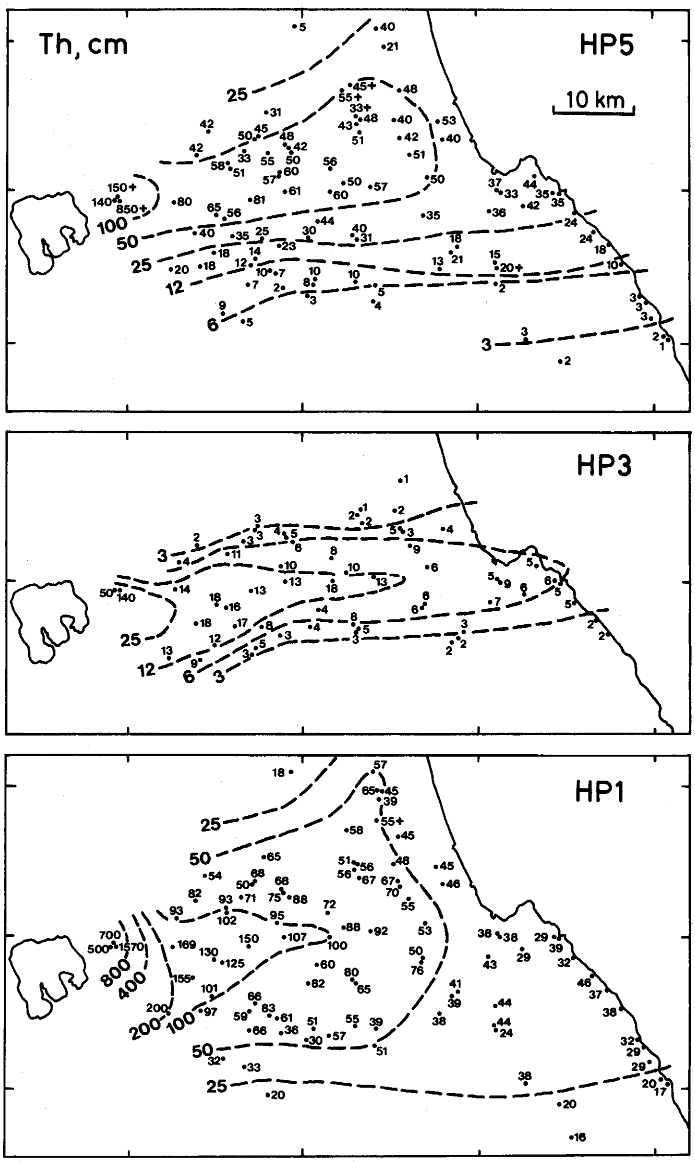


Fig. 4 Isopach maps of the six beds composing the Hachinohe phreatoplinian ash (after Hayakawa, 1983)
Values are in cm.

Pumice beds

The maximum diameters of pumice fragments (MP) and lithic fragments (ML) are measured for the HP2, HP4, and HP6 pumice beds (Fig. 7). The areas enclosed by isogrades are comparable to or even surpass those of plinian deposits from the same volcano (Hayakawa, 1985).

The HP4 pumice is distinctive because it is very rich in lithic fragments and both of

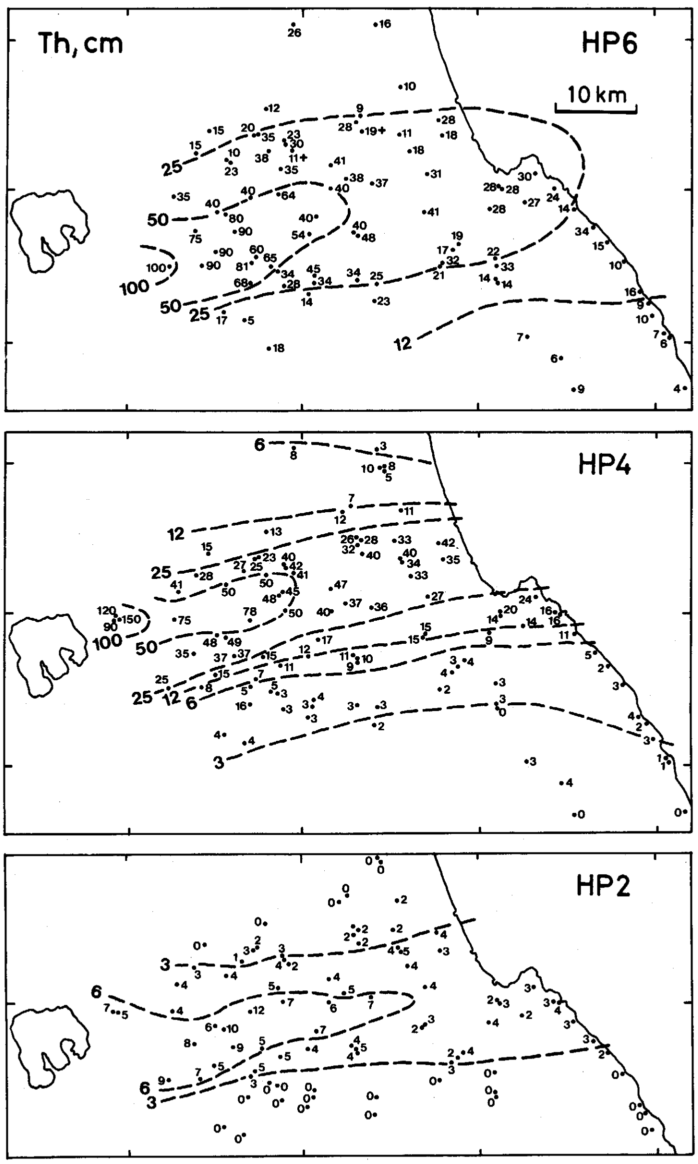


Fig. 4 (continued)

the MP and ML are the largest among pumice beds. Surfaces of pumice fragments are thinly coated with fine ash and a small amount of accretionary lapilli are found among pumice lapilli in the HP4 bed (Fig. 8). In the HP6 pumice bed, a stratification is obvious that is manifested by beds of clasts of different grainsizes. A few of them are accumulation of accretionary lapilli. Pumice fragments of the HP6 are subrounded.

The HP2 pumice bed is thin. The maximum thickness does not exceed 12 cm throughout the distribution. Nevertheless it is widely dispersed. The areas enclosed by the MP and ML isogrades are slightly smaller than those for HP4 and comparable to those for HP6. The normal size-grading is ubiquitously seen in the HP2 bed, indicating that the HP2 pumice is a product from a short-lived, perhaps less than an hour, eruption column of high altitude.

In addition to the above-mentioned three beds, there are many but thin pumice beds in the lower part of the HP1 ash and two more beds in the HP5 ash. The latters are composed of crystals and lithics of sandsize. The uppermost bed in the HP1 ash is named HP1.8 pumice. The dispersal is shown in Fig. 9. In places it surpasses the HP2 bed in both of the MP and ML values.

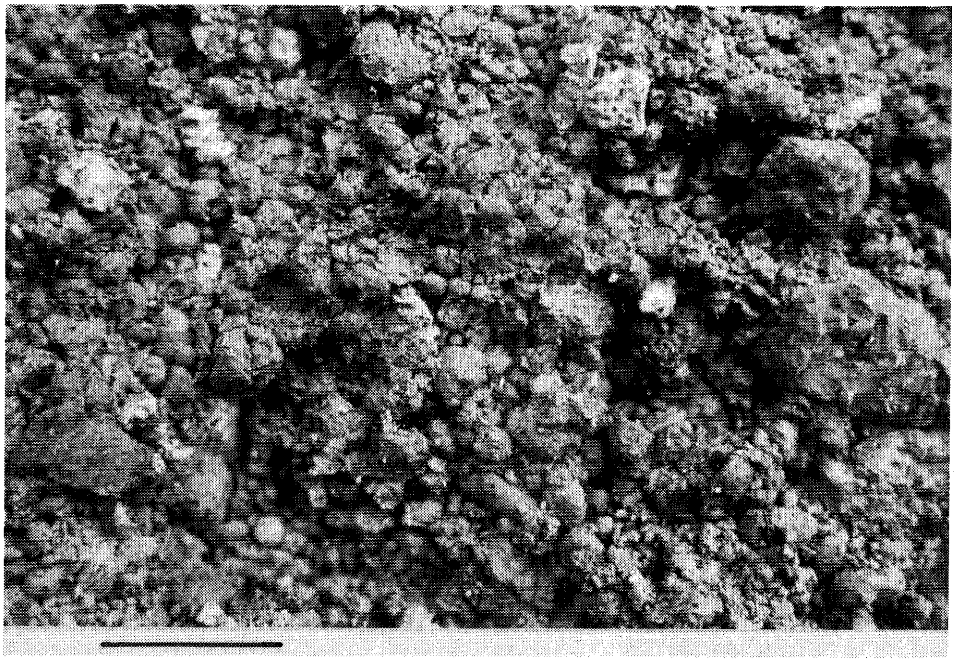


Fig. 5 Closely packed accretionary lapilli with open matrix in the upper part of HP1 ash bed, at Takizawa, 28 km E of the source
Some large lapilli are ash-coated pumice fragments. Scale is 20 mm long.

3. Grainsize Characteristics

The grainsize characteristics of the Hachinohe ash at Ishizawa, 34 km E of the source, are shown in Fig. 10. Three ash beds have almost the same grainsize populations with the median diameter of about 0.045 mm and the mode of about 0.020 mm. The populations also remain nearly constant with increase of distance from the source (Fig. 11b). Some 50 wt.% is composed of fine ash. However, a small degree of fractionation is observed that ash particles of 1mm to 1/4 mm increase away from the source while those finer

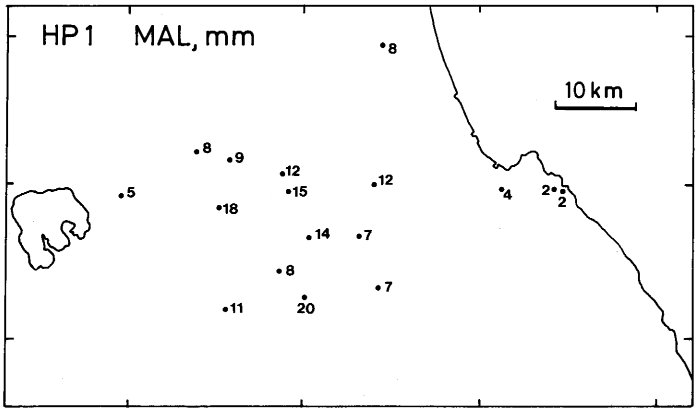


Fig. 6 Map showing the maximum diameter of accretionary lapilli (MAL) in the upper part of the HP1 ash bed (after Hayakawa, 1983)
Note that the size does not increase toward the source. Values are in mm.

than 1/16 mm decrease. It offers a striking contrast with those of plinian pumice deposits. The Nambu plinian pumice of 8,500 years B.P. of the same volcano, for example, shows a strong fractionation away from the source. Fines are progressively removed (Fig. 11a).

The coarse-tail grading of ash beds shown in Fig. 10 is created by two different kinds of clasts. Some are pumice lapilli embedded in fine ash and the others are core fragments of accretionary lapilli disintegrated during the sieving.

Pumice beds show a bimodal distribution. The major coarse mode is due to pumice and lithic lapilli. The secondary fine mode is due to fine ash derived from disintegrated accretionary lapilli and fine ash originally attached to pumice fragments. Contents of fine ash (<1/16 mm) are 17, 14, and 11 wt.% for the HP2, HP4, and HP6 beds, respectively. Bimodal grainsize distributions in fallout deposits have been reported by Brazier *et al.* (1983) from the 18 May 1980 Mount St. Helens deposit, 1979 Soufriere ash of St. Vincent, and others.

4. Mode of Eruption

The fine grained nature and wide dispersal clearly indicate that the ash beds are characteristic of the phreatoplinian deposits (Self and Sparks, 1978), formed by interaction of water and silicic magma during explosive eruptions. The initial contact of external water with erupting magma and the volume ratio of water to magma are the most important factors governing development of the phreatomagmatic eruption (Sheridan and Wohletz, 1981). Wohletz (1983) has determined that the maximum abundance of fine ash produced by eruptions attains over 30 wt.% when the interaction reaches an explosive maximum, which occures with interactions of virtually equal volumes of magma and water.

Consider the volume relationship between the erupted magma and the lake water. The

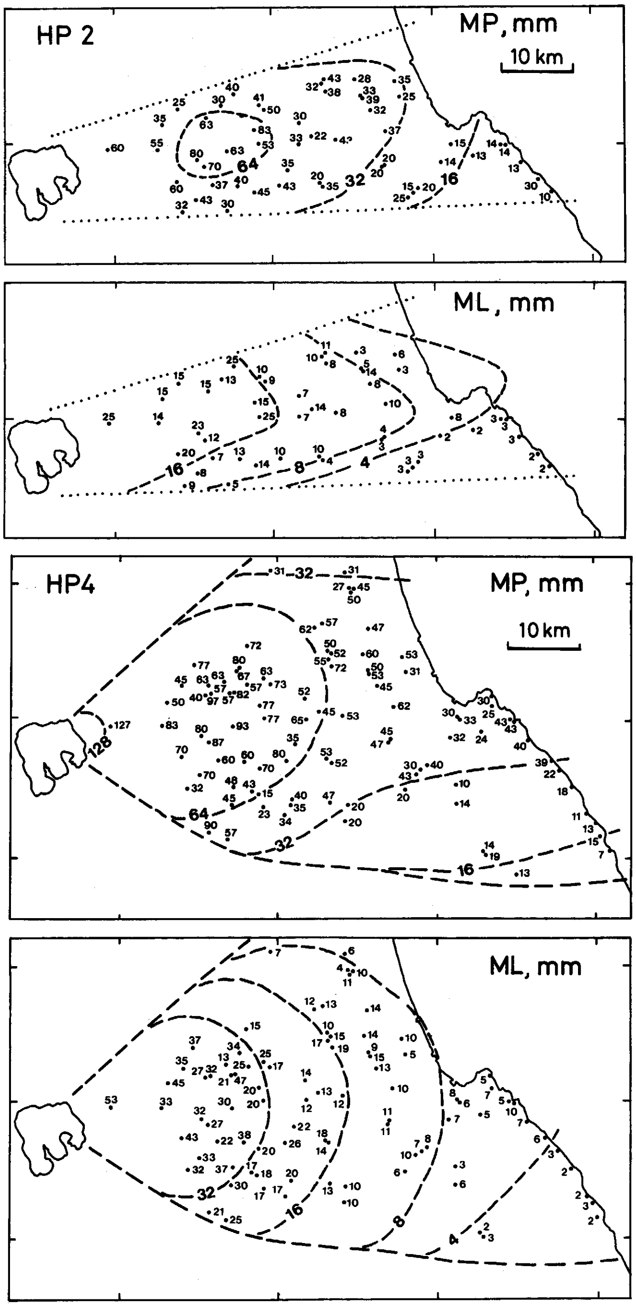


Fig. 7 MP and ML isograde maps for the HP2, HP4, and HP6 pumice beds (after Hayakawa, 1983)
MP is the average maximum diameter of the three largest pumice fragments seen at each exposure. ML is that of lithic fragments. Values are in mm.

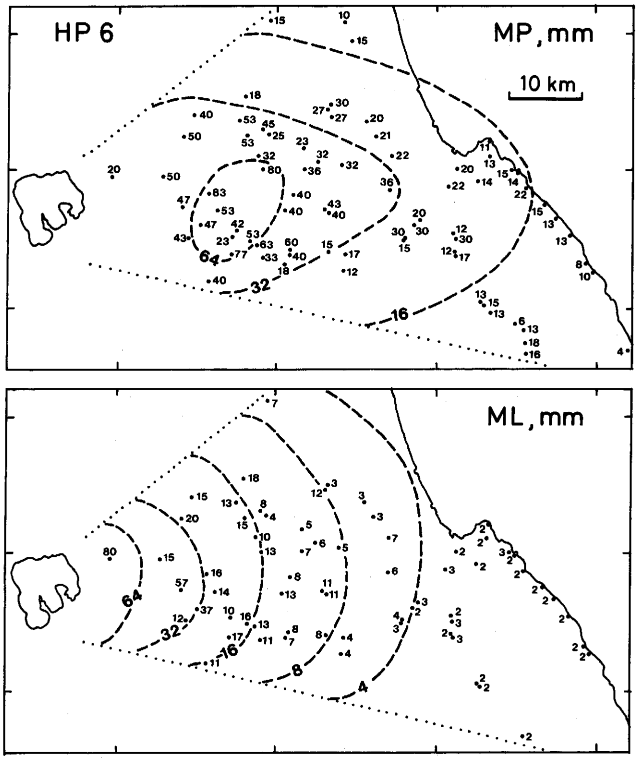


Fig. 7 (continued)

total mass of the ash beds (HP1, HP3, and HP5) has been estimated as 8.5×10^{12} kg (Hayakawa, 1985). Assuming the density of 2,300 kg/m^3, volume of the erupted magma is calculated to be 3.5×10^9 m^3. This is comparable to 4.8×10^9 m^3 of water presently contained in the lake. It is possible and very likely that the lake water was responsible for the phreatomagmatic character of the Hachinohe ash.

The pumice beds may be classified into plinian deposits, derived from magmatic eruption columns higher than about 10 km. However, some unique features indicate a diversity from common plinian products: (1) a pink thermal coloration produced by the oxidation of iron is never seen inside large pumice fragments, (2) surfaces of pumice fragments are thinly coated with fine ash, and (3) a number of accretionary lapilli are found in the beds. These lines of evidence suggest that, even in pumice eruptions, a phreatomagmatic process was partly effective in the magma fragmentation.

5. Mode of Deposition

The terminal fall velocity of an ash particle less than 0.03 mm in diameter is less than 0.1 m/s (Wilson and Huang, 1979). The fall time of the particle from the height of 10 km is calculated to be more than 200 min (Wilson, 1972), while it may well be displaced

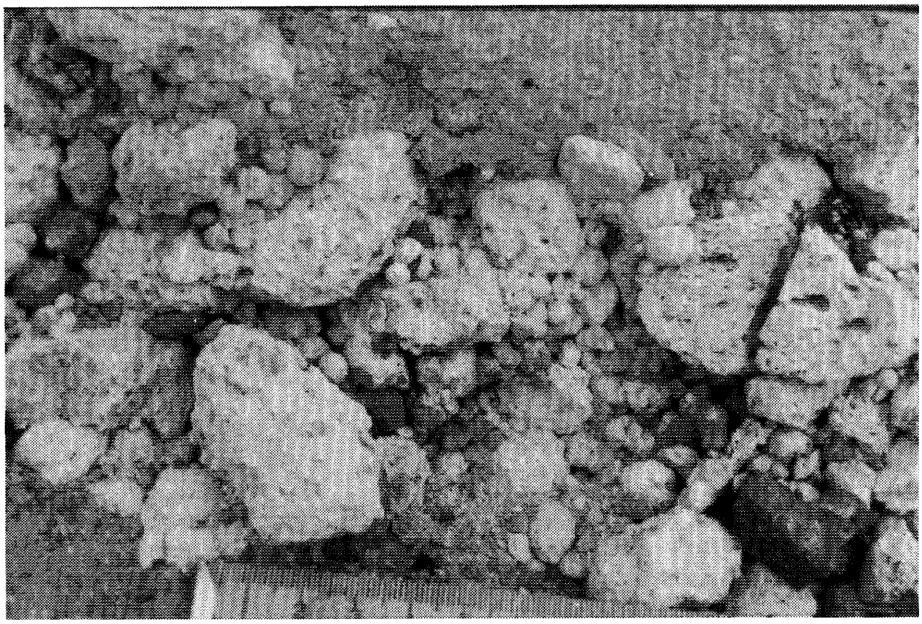


Fig. 8 Accretionary lapilli enclosed in the HP4 pumice bed at Ken'yoshi, 36 km E of the source
Individual unit on scale is 1 mm.

farther than 100 km from the source by the wind. It is deduced that fine ash particles of the Hachinohe ash near the source area were not decended as individually separate particles but in the form of accretionary lapilli or attaching to pumice surfaces.

Falling of fine ash particles as accretionary lapilli or particle aggregates, which are fragile aggregates easy to distintegrate on impact with the ground, has been observed during many recent explosive eruptions (Table 1). In Soufriere of St. Vincent accretionary lapilli on 26 April 1979 fell completely dry and slightly warm to touch, in contrast to the fall on 22 April where the accretionary lapilli were damp (Brazier *et al.*, 1982). Particle aggregates of Usu on 8 August 1977 fell as raindrops (Suzuki *et al.*, 1982). Those of Aso on 5 November 1989 were dry enough to be removed by car wipers. Figure 12 is a photograph of freshly fallen accretionary lapilli of Izu Oshima on 16 November 1987.

The premature fallout of fine ash in the form of accretionary lapilli or particle aggregates will be an inevitable depositional process operating in phreatomagmatic eruption clouds (Walker, 1981; Carey and Sigurdsson, 1982; Brazier *et al.* 1983; Hayakawa, 1983). Accretionary lapilli of the Hachinohe ash are so fragile that they are very easily disintegrated when held between the fingers. Nevertheless all of the lapilli on the surface of outcrops are nearly ideal spheres. They were not deformed on impact with the ground. It is supposed that the lapilli were frozen up during the descent from the eruption cloud. They may have fallen like hailstones. Accretionary lapilli in the Shimajiri group, Miocene to Pleistocene marine sediments in Okinawa, have been reported as volcanic hailstones by Kato (1986).

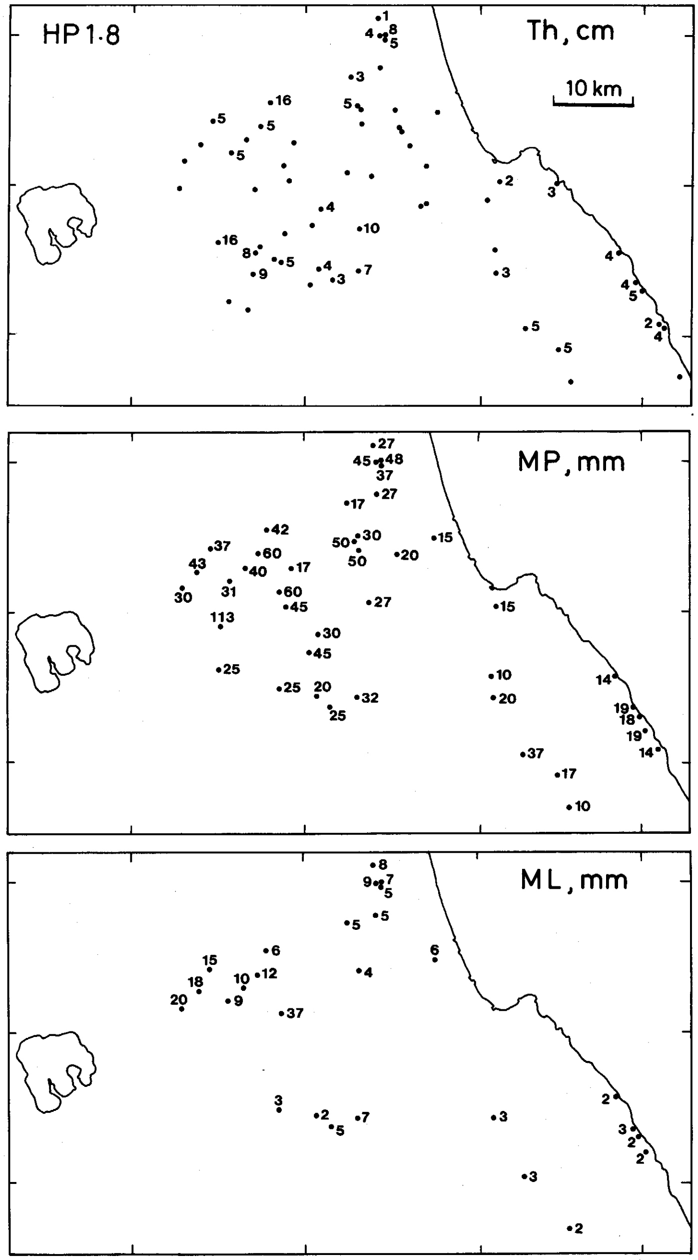


Fig. 9 Isopach map (in cm) and MP and ML isograde maps (in mm) of the HP1.8 pumice bed
In the isopach map, points with no value represent thicknesses less than 5 cm.

6. Volcanologic Interpretation of the Hachinohe Ash Sequence

Alternating beds of ash and pumice suggest that the Hachinohe ash is a product from a series of complex eruptive events. An eruption scenario is speculated as follows:

A lake filling the caldera depression is assumed to have existed before the Hachinohe eruption because an older large-volume ignimbrite of 25,000 years B.P. is distributed around the caldera (Oike and Nakagawa, 1979). The vent of the Hachinohe eruption opened on this lake 13,000 years ago. The style of the eruption was phreatoplinian formed by interaction of water and magma. Access of lake water to the vent was not so effective in the initial stage that a number of thin pumice beds, products of a relatively magmatic phase, were intercalated in the lower part of the HP1 ash.

In a few hours a steady state phreatoplinian eruption column was established. The product is the upper part of the HP1 ash, a monotonous bed composed of closely packed

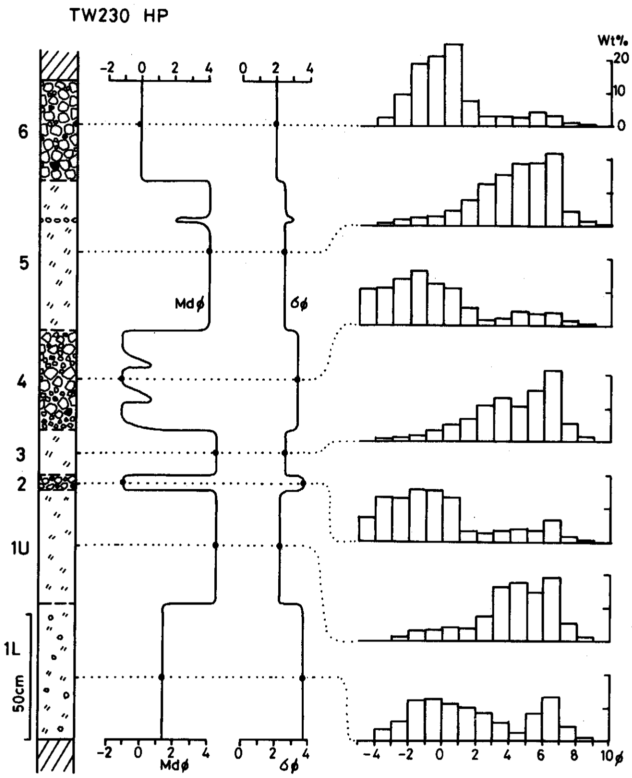


Fig. 10 Diagram showing grainsize characteristics of the Hachinohe ash at Ishizawa, 34 km E of the source
Mdϕ is median diameter, and $\sigma\phi$ is standard deviation; both in ϕ unit (*e.g.* -1ϕ=2mm, 0ϕ=1mm, 1ϕ=1/2mm).

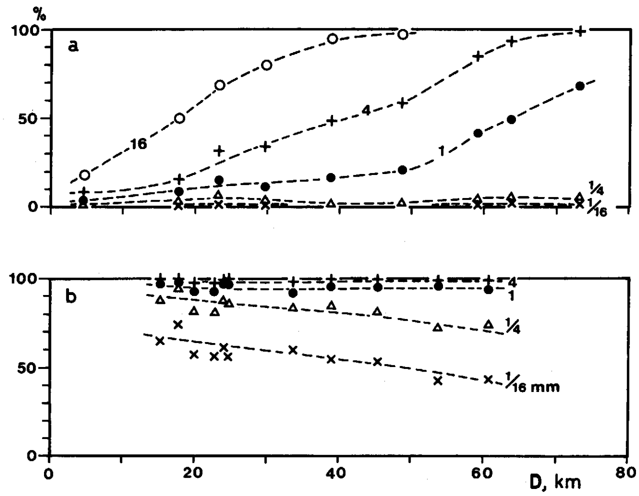


Fig. 11 Cumulative weight percentage of material finer than selected grainsizes, in mm, for (a) the Nambu pumice and (b) the HP1 ash, plotted against distance from the source (after Hayakawa, 1983). Note the strong cotrast between them.

accretionary lapilli. Discharge rate of magma occasionally rose so that mass ratio of water to magma became lower than the ratio of an explosive maximum, when the style was converted into a relatively magmatic eruption. Pumice beds of HP1.8, HP2, and HP4 are products of those events. Abundant lithic fragments in the HP2 and HP4 beds imply enlargement of the vent radius.

A stable phreatoplinian eruption column was again sustained for a few hours, feeding accretionary lapilli of the HP5 ash bed. Then discharge rate of magma gradually declined. The transition from the HP5 ash to the HP6 pumice may indicate the time when most of the lake water had been used up. The pronounced bedding and roudness of pumice fragments suggest that the height of the HP6 eruption column heavily fluctuated due to a intermittent interaction between magma and groundwater in conduit.

Coincidently with onset of caldera subsidence, the eruption column collapsed and

Table 1. Recent eruptions when falling of accretionary lapilli or paticle aggregates were observed.

Eruption	Form	Reference
Usu 1977.8.8	PA	Suzuki *et al.* (1982)
Ontake 1979.10.28	PA	Kobayashi (1979)
Soufriere of St. Vincent 1979.4.22 and 26	AL	Brazier *et al.* (1982)
Mount St. Helens 1980.5.18	PA	Sorem (1982)
Asama 1982.4.26	PA	Aramaki and Hayakawa (1982)
Sakurajima 1983.5.22	AL	Tomita *et al.* (1985)
Izu Oshima 1987.11.16	AL	Hayakawa and Shirao (1988)
Aso 1989.11.5	PA	(Author's own observation)

AL: accretionary lapilli; PA; particle aggregates pyroclastic flows were generated from newly formed ring (?) vents. The pyroclastic flow eruption ended in another moment resulting in an ignimbrite sheet of about 40 km^3 around the caldera. I suspect that the total duration of the eruption falls within several to several tens hours.

Fig. 12 Accretionary lapilli on the pavement, 3 km E of the source, found 5 hours after the explosion of the Izu Oshima volcano. Photo by Motomaro Shirao on 16 November 1987. Top of a ball-point pen for scale.

7. Conclusions

The Hachinohe ash is a large-volume, fine grained, and widely dispersed fallout tephra from the Towada volcano. It was formed by interaction of lake water and rhyodacitic magma during the explosive eruption. It is composed of alternating beds of ash and pumice reflecting a complex eruptive sequence. Pumice beds document the attainment of relatively magmatic phases during phreatomagmatic explosions. Closely packed accretionary lapilli in ash beds and ash-coated pumice fragmants clearly indicate that fine ash particles of the Hachinohe ash descended through the air in the form of accretionary lapilli or attaching to pumice surfaces. It is concluded that the Hachinohe ash is a candidate for a type deposit of phreatoplinian eruptions.

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I wish to dedicate this article to Professor Sohei Kaizuka in commemoration of his retirement from Tokyo Metropolitan University.

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