The Mode of Eruptions and Their Tephra Deposits

Tetsuo KOBAYASHI[1] and Mitsuru OKUNO[2]

[1] Earth and Environmental Sciences, Faculty of Science, Kagoshima University
1-21-35 Korimoto, Kagoshima, 890-0065 Japan
E-mail: koba@sci.kagoshima-u.ac.jp
[2] Department of Earth System Science, Faculty of Science, Fukuoka University
8-19-1 Nanakuma, Jonan-ku, Fukuoka, 814-0180 Japan

Abstract

In accordance with the physical properties of the magma and the scale of eruption, the types of explosive eruptions are classified as follows: hawaiian, strombolian, vulcanian, sub-plinian, and plinian eruptions for magmatic eruptions; and surtseyan and phreatoplinian for phreatomagmatic eruptions. The mode of transportation of tephra is divided into the three categories of fall, flow, and surge. Each tephra layer has a characteristic depositional structure, produced not only by the mode of eruption but also by the transportation mode. As tephra layers are deposited during active periods, while loam layers accumulate during quiescent periods, a thick tephra sequence consisting of alternating tephra and loam layers will form around an active volcano.

The preservation or erosion of tephra depends on not only the thickness of the deposits but also the cohesion of the tephra and the environment of deposition. Where thin tephra layers are deposited, they can become difficult to identify as individual tephra layers, due to bioturbation of the soil. In such cases, we have to use different techniques to correlate the tephra not only by the morphological feature of the pumice grains, but also by the petrological properties of the pumice, glass shards and phenocrysts.

Key words: eruption, flow, magmatic, phreatomagmatic, surge, tephra

1. Introduction

Depending on the chemical and physical nature of the erupting magma and the environment around the vent (dry or wet), the mode of eruption varies widely. The solidified and/or molten particles of magma which become fragmented during the eruption and ejected above the vent are generally called tephra. (Thorarinsson, 1944). The eruption style and the weather conditions are main controlling factors of transportation and dispersal of the tephra, which normally show a wide distribution. As tephra accumulates on the ground instantaneously over the geological time scale, it is very effective as a key marker in geological successions. Tephrochronology is one division of volcanology, and is gaining important value in various scientific fields, such as the correlation of tephras with the age estimations of archeological sites. However, if the tephra is not preserved well, various research techniques have to be applied to identify the tephra. In this article, we describe the modes of eruption, the sedimentary structures of representative tephra deposits and field occurrence of tephra sequences.

2. Mode of Eruptions

An eruption occurs when magma migrates upward, often driven by expansion of dissolved gas, and is discharged on to the surface of the earth. When ground water is heated by ascending magma, enormous amounts of vapor may be formed causing steam explosions. In this type of eruption, magma may not reach the surface of the earth, and ejected materials are cold accessory or accidental rocks, which are sometimes hydrothermally altered. Magmatic (juvenile) material may not be ejected at all. This is generally called a phreatic eruption (Barberi *et al.*, 1992).

On the other hand, magmatic eruptions mainly eject fragmented magma. Modes of eruptions vary widely depending on the physical and chemical nature of the magma. The amount of erupted material also varies widely, sometimes exceeding 100 km^3 in bulk volume.

Phreatomagmatic eruptions occur when magma interacts with near-surface water, and this type is sometimes more explosive than normal magmatic eruptions. Phreatomagmatic eruptions most commonly involve basaltic magma, and often produce lateral blasts around the crater. Phreatomagmatic eruptions occur especially in water-rich environments such as seashores, shallow lakes, crater lakes, caldera lakes, etc. (White and Houghton, 2000).

Explosive magmatic eruptions are classified in Fig. 1, and divided into five types: hawaiian, strombolian, vulcanian, sub-plinian and plinian, based on the scales of the explosiveness and dispersal (Walker, 1973). Explosiveness and dispersal are correspondent to degree of fragmentation of the deposit and height of eruption column, respectively. Figure 2 shows representative sketch of each eruption type (Moriya, 1992). When the viscosity of the magma is low, a mild eruption (hawaiian and strombolian) will occur. Eruptions become more violent (vulcanian to plinian) as the viscosity of the magma increases. Plinian eruptions are the most explosive, and discharge large quantities of pumice (Walker, 1981). Plinian eruptions generally involve silicic magma, although some basaltic plinian eruptions are known (Walker and Croasdale, 1972). Although vulcanian eruptions sometimes occur as a kind of phreatomagmatic eruption (Self *et al.*, 1979), phreatomagmatic implications are not included in Japanese terminology (Moriya, 1992). Hence, violent explosions accompanied by shock waves and a high eruption column are classified as vulcanian in Japan.

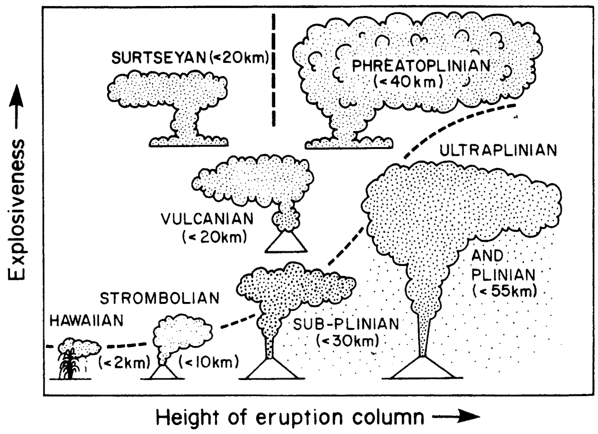


Fig. 1 Diagram explaining eruption column height and 'explosiveness' (after Cas and Wright, 1987).

Large eruption columns commonly reach up to several tens of kilometers into the atmosphere. Ash and pumice are then carried by the prevailing winds before falling to the surface of the earth. In some cases, the eruption column does not rise completely,

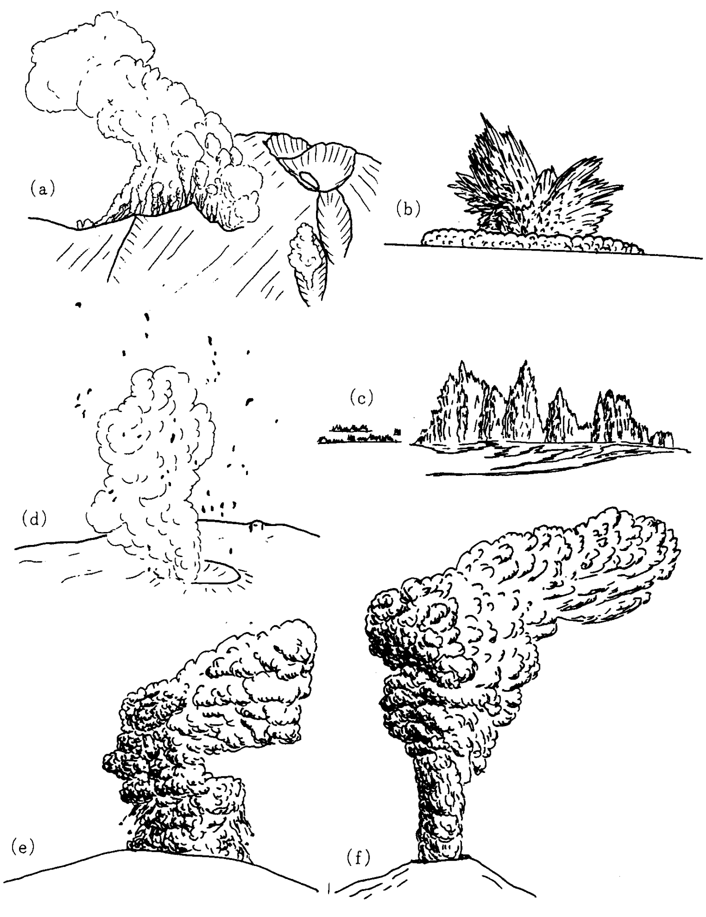


Fig. 2 Representative sketches of eruption columns: (a) phreatic, (b) phreatomagmatic (c) hawaiian, (d) strombolian, (e) vulcanian and (f) plinian eruptions (after Moriya, 1992).

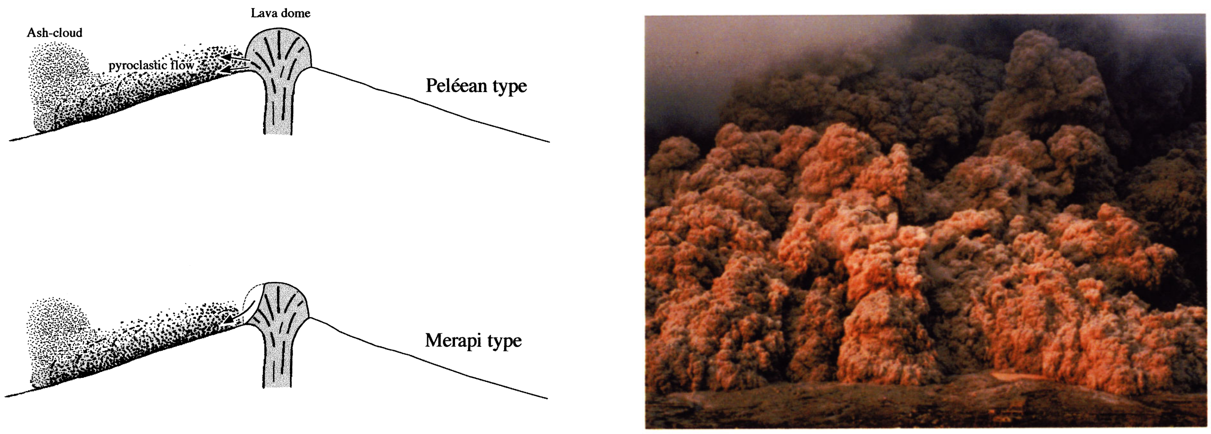


Fig. 3 Model of generation of pyroclastic flows from lava domes and a tremendous pyroclastic flow cascading down the slope of Unzen volcano, 1993 (Volcanological Society of Japan).

and a partial or full column collapse can occur, flowing down the slopes of the volcano, as a pyroclastic flow. These flows are common in plinian, sub-plinian, and vulcanian eruptions. The deposit consists of vesiculated pumice and/or scoria and ash. Depending on the components, they are classified as pumice flows or scoria flows, and are generally called ignimbrite.

Pyroclastic flows also occur when a lava dome and/or lava flow explodes or gravitationally collapses (Fig. 3). This mode of eruption is called a Peléean or Merapi type (Macdonald, 1972). The pyroclastic flows thus formed are mainly composed of dense essential material, and are called block-and-ash flows.

3. Classification of Tephra

Based on the mode of transportation, tephra is classified into three types of deposits: fall deposits, pyroclastic flow deposits, and pyroclastic surge deposits (Wright *et al.*, 1980). The resulting sedimentary structures of these three are quite different from each other (Fig. 4).

3.1 Fall deposits

Fall deposits are formed from an eruption column which rises high into the atmosphere to generate an eruption cloud which disperses downwind. Since winnowing of particles occurs during transportation, the fall deposits are generally well sorted, and show mantle bedding (Fig. 4-a). This good sorting normally produces clast-supported deposits. Each clast is angular to sub-angular in shape. Due to free spaces among the clasts, the deposits are usually very loose and tend to collapse (Fig. 5-a). Although grain size distribution is mainly controlled by the height of the eruption column and the velocity and direction of atmospheric winds (Walker, 1973), there is a general tendency for coarse material to accumulate in proximal areas, while finer material is carried to distal areas.

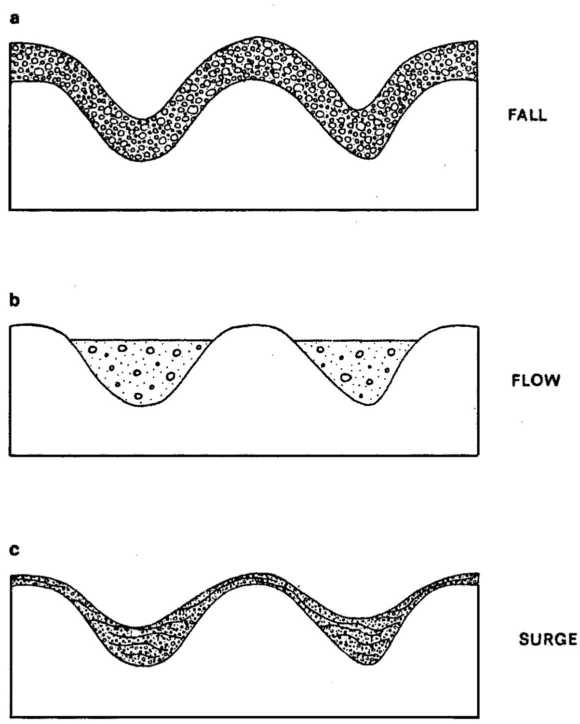
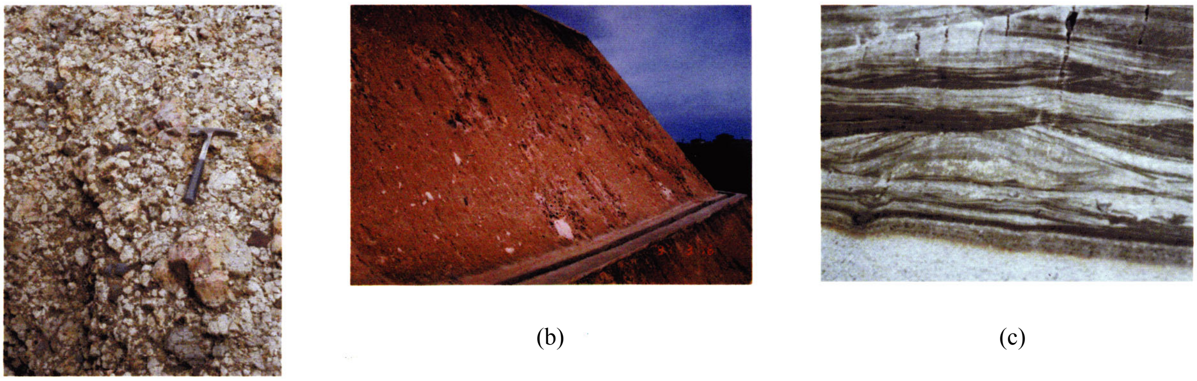


Fig. 4 Geometric relations of the three main types of pyroclastic deposits (after Wright *et al.*, 1980).

3.2 Pyroclastic flow deposits

Pyroclastic flows are a mixture of incandescent solid clasts and gas, which flow down slopes into topographic lows such as valleys and depressions as a kind of density flow (Fig. 4-b). Large volume pyroclastic flows spread in the shape of a fan at the foot of the volcano, and can bury valleys to form a vast pyroclastic flow (ignimbrite) plateau. Pyroclastic flow deposits normally consist of large clasts in an ash matrix, and are generally massive and poorly sorted. Large fragments are normally rounded due to abrasion during the flow (Fig. 5-b).



(b) (c)

(a)

Fig. 5 Photos of representative outcrop of each tephra.
(a) Bunmei pumice fall deposit of Sakurajima volcano, (b) Ito ignimbrite from the Aira caldera,
(c) Yamakawa base surge deposit, Ibusuki volcanic area.

3.3 Pyroclastic surge deposits

Pyroclastic surges are also a kind of density current which are dilute, low particle concentration, turbulent flows. The deposits are generally topographically controlled, but they tend to mantle topographic highs as thin layers. They are composed mainly of particles sand-sized or less, and are generally better sorted than pyroclastic flow deposits. They sometimes show unique sedimentary bed forms such as dune-forms, low angle cross stratification, etc. (Figs. 4-c and 5-c).

Two types of pyroclastic surges are well known: ash-cloud surges and base surges. Ash-cloud surges are formed by the turbulent elutriation of fine ash from the margins of pyroclastic flows, and flow outward from the main flow. They normally have a high temperature, and can burn vegetation to charcoal. Base surges are direct lateral blasts that mainly occur during phreatomagmatic explosions. Because cold surface water is involved, the temperatures of base surges are generally low compared with those of ash-cloud surges, so the deposits are generally wet and sometimes muddy and sticky.

4. Distribution and Occurrence of Tephra

When plinian or sub-plinian eruptions occur, thick pumice and/or scoria may accumulate around the foot of the volcano. As the eruption column reaches more than 10-km height, tephra is normally carried to the east of the vent owing to the prevailing westerlies (Fig. 6). These tephra deposits may be divided into sub-units that have different facies, color, grain size, etc. These conspicuous changes are mainly generated from different eruption columns; which occurred at intervals of a few hours to several months. Further subdivision may be possible in each sub-unit, which may be formed either by the fluctuation of a single eruption column, or by eolian fractionation during transportation.

When a large scale caldera-forming eruption occurs, voluminous co-ignimbrite ash-fall deposits (Sparks and Walker, 1977) may be elutriated from the pyroclastic flows, and spread over vast areas. These wide-spread deposits form important key-tephras in geological successions (Fig. 7). Co-ignimbrite ash is composed mainly of fine, vesiculated glass shards; hence, it is easy to distinguish from other tephra.

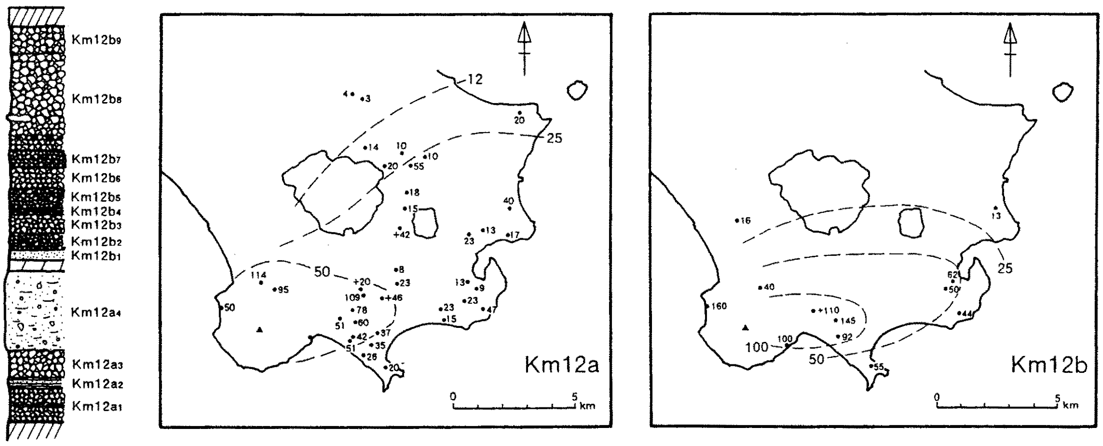


Fig. 6 Stratigraphic column and isopach maps for Km12 consisting two overlapping tephra from eruptions in AD 874 and AD 885 (after Fujino and Kobayashi, 1997).

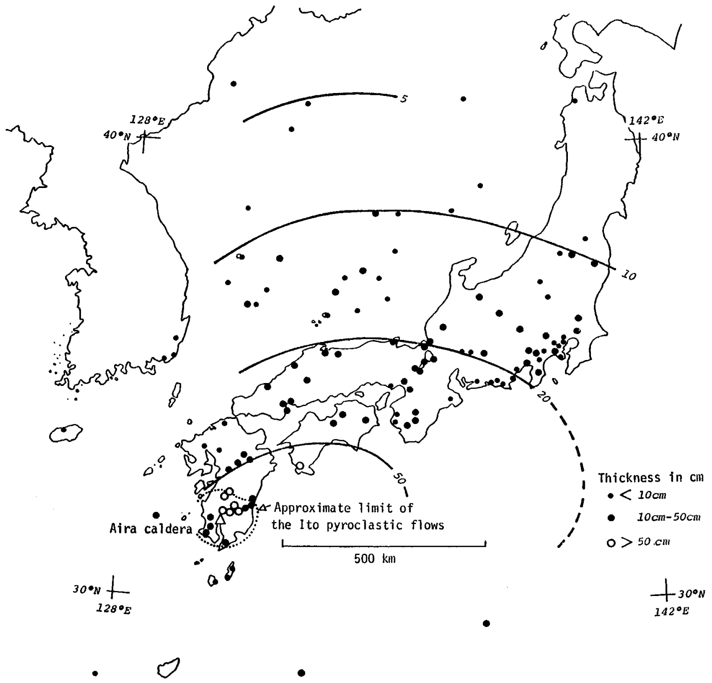


Fig. 7 Isopach map of the Aira-Tn (AT) ash-fall deposit (after Machida and Arai, 1983). AT ash is one of the biggest wide-spread tephra of the Late Quaternary age in Japan.

Distal tephra of vulcanian and strombolian eruptions is generally fine-grained, so it normally settles just like fine dust, and is easily reworked. As the volume of tephra of each eruption is not large, the tephra is easily mixed with soil, and becomes obscure. However, if an eruption episode is sustained for a long period, ash will accumulate gradually and form a distinct ash layer. As tephra of this type is dispersed to any direction according to the seasonal wind directions, the isopach pattern of the total thickness of tephra can show an almost concentric semi-circular distribution centering on the crater (Fig. 8). As the sand-size portion tends to remain during any re-deposition process, the resulting deposit can be called a volcanic sand deposit.

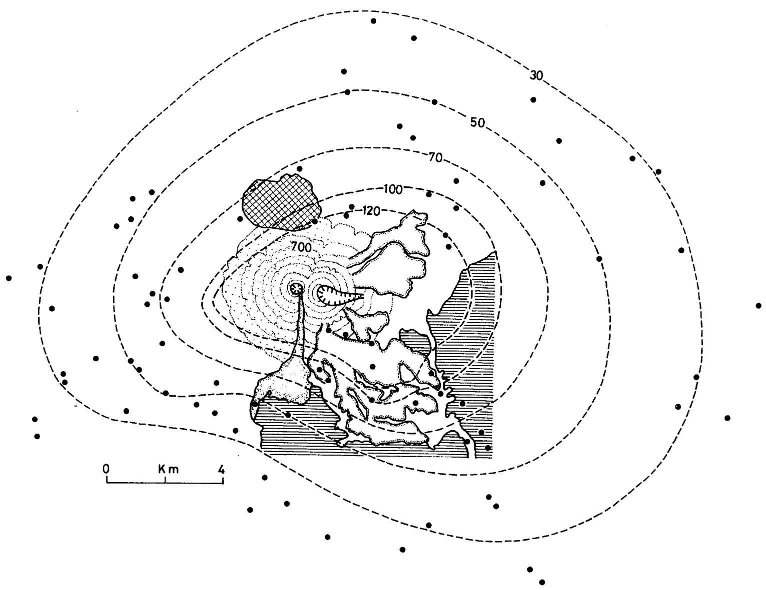


Fig. 8 Isopach map of Ushinosune ash from Takachihonomine of the Kirishima volcano group (after Inoue, 1988). Semi-circular distribution is typical for the tephra of intermittent vulcanian eruptions.

5. Deposits Formed during Dormant Periods

Once an eruption episode has ceased, it is common for many volcanoes to enter a long quiescent period, which may continue for hundreds to more than several thousand years. During that period, volcanic soil is formed on the tephra layer. In contrast to tephra, volcanic soil is derived essentially from eolian dusts, and accumulates very slowly. The soil mainly consists of fine materials less than sand-sized, and generally shows no internal stratification. As the soil usually contains abundant humus, it is black in color, and called humic soil. If the tephra is much older than twenty thousand years, humic soils will be weathered and change to yellow-brown soils, which are collectively known as "loam" in Japan (Nakamura, 1970; Hayakawa, 1995).

As mentioned above, tephra and loam are deposited during eruptive periods and non-eruptive periods, respectively. Many cycles of such layers are observable around the foot of stratovolcanoes (Fig. 9). The thickness of the loam sandwiched between the tephra layers tends to be in direct proportion with the length

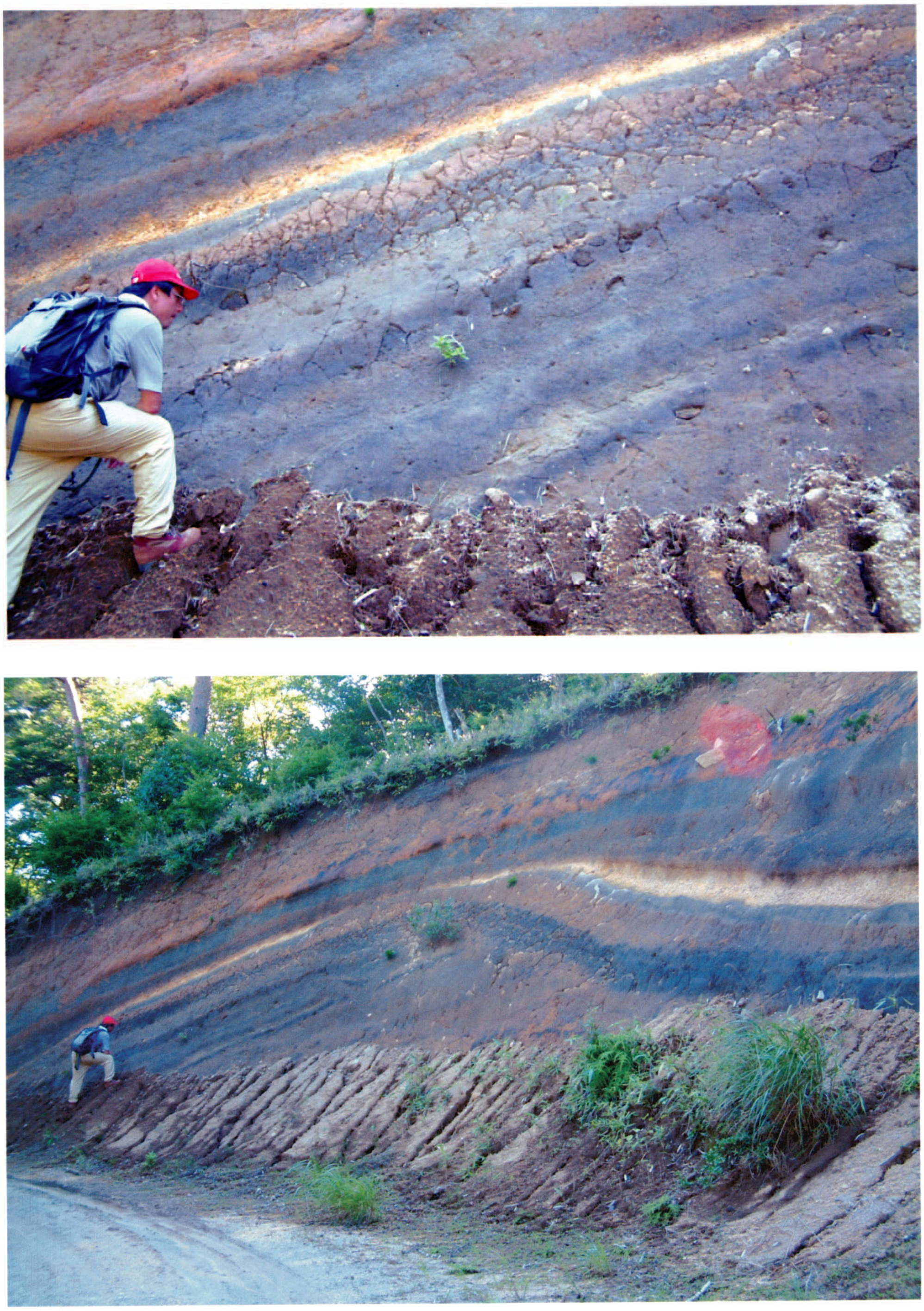


Fig. 9 Sequence of many tephra layers at the foot of Onamiike, Kirishima volcano group.

of the dormant period, indicating that the thickness of the loam steadily increases at a constant rate. If there are two tephra layers whose eruption ages were already known, the eruption age of intercalated tephra between them can be roughly estimated by the proportion of thickness of upper and lower loam layers.

6. Conditions for Preservation of Tephra

Tephra settled on land is easily eroded by wind and redeposited at different places. Tephra deposits are also mixed with soils due to bioturbation by invasion of plant roots and activities of small insects, worms, etc. The preservation state of tephra is influenced by its location in the topography, the vegetation, thickness and grain-size of the tephra, deposition frequency, etc.

In relation to topography, flat ground is more conducive to preservation of tephra than sloping ground. However, there is a possibility of redeposition onto lowlands or depressions from surrounding high areas. In relation to vegetation, grassy fields and swamps are better than arid areas for preservation of tephra. The vegetation protects tephra from erosion by wind or rain, and provides good conditions for the deposition of eolian dusty material. Peat swamps provide an ever better preservation site for tephra.

It is generally thought that a thick tephra tends to be preserved for a long time. However, even if thin, a sticky tephra such as clayey ash will be preserved in many cases. Wet tephra, often associated with phreatomagmatic eruptions tends to change to consolidated tephra, which is also very resistant to erosion. Moreover, even thin tephras are well preserved if buried quickly beneath other eruptive products. A good example is that plinian pumice underneath pyroclastic flow deposits is well preserved. Thin tephra layers accumulating during the early stages of a sustained eruption episode are also likely to be preserved, because they are quickly buried by successive tephra accumulation. For the same reason, a wide-spread tephra tends to be preserved at different active volcanic fields.

7. Recognition and Correlation of Tephra

Thick proximal tephra often shows particular depositional stratification such as reverse grading, alternation of coarse and fine layers, etc. However, at distal locations, a thin, disturbed tephra layer becomes obscure, being dotted sparsely at the specific horizon, and finally becoming difficult to identify as a discrete layer. Even in such a case, we may be able to correlate it to the apparent tephra at a neighboring field by tracing the stratigraphic horizon and the change of grain size. However, there is a limit to the observation and pursuit of traces of tephra in the field. It is therefore necessary to correlate tephra not only by morphological features of pumice grains, but also by petrologic properties, such as the mineral assemblage, refractive index and chemical composition of glass shards and phenocrysts (Machida and Arai, 1992).

8. Conclusion

Features of tephra were described in this article not only by the mode of eruption, but also by the mode of transportation. We also showed the difference between strata formed during eruptions and non-eruption terms (tephra layers vs. loam layers), and explained the conditions under which tephra is preserved and methods of identification of tephra.

Although tephra is an effective medium for studying the eruptive history of volcanoes, it is also likened to fossils that include the depositional environment of those days. Further research on the influence of tephra on the environment must also be done in the near future.

Acknowledgements

The Authors would like to express their appreciation to Prof. M. Taniguchi for his invitation to contribute to this special issue. We also thank Prof. T. Nakamura, Prof. H. Moriwaki, and Mr. H. Naruo for helpful collaboration.

References

Barberi, F., A. Bertagnini, P. Landi and C. Principe (1992) A review on phreatic eruptions and their precursors. *Journal of Volcanology and Geothermal Research*, 52: 231-246.

Cas, R. A. F. and J. V. Wright (1987) *Volcanic successions: modern and ancient: a geological approach to processes*. Allen and Union, London.

Fujino, N. and T. Kobayashi (1997) Eruptive history of Kaimondake volcano, southern Kyushu, Japan. *Bulletin of the Volcanological Society of Japan*, 42: 195-211. (in Japanese with English abstract)

Hayakawa, Y. (1995) Characteristics of Japanese loam, and its eolian origin. *Bulletin of the Volcanological Society of Japan*, 40: 177-190. (in Japanese with English abstract)

Inoue, K. (1988) The growth-history of Takachiho composite volcano in the Kirishima volcano group. *Journal of Mineralogy, Petrology and Economic Geology*, 83: 26-41. (in Japanese with English abstract)

Macdonald, G. A. (1972) *Volcanoes*. Prentice-Hall, Englewood Cliffs, New Jersey.

Machida, H. and F. Arai (1983) Extensive ash falls in and around the Sea of Japan from large late Quaternary eruptions. *Journal of Volcanology and Geothermal Research*, 18: 151-164.

Machida, H. and F. Arai (1992) *Atlas of tephra in and around Japan*. University of Tokyo Press, Tokyo. (in Japanese)

Moriya, I. (1992) *Interpreting Volcanoes*. Iwanami-shoten, Tokyo. (in Japanese)

Nakamura, K. (1970) Akatsuchi or so-called loam and eruptive phenomena. *Zeitschrift fur Bimssteinskunde (Karuishigaku-zasshi)*, 3: 1-7. (in Japanese with English abstract)

Self, S., L. Wilson and I. A. Nairn (1979) Vulcanian eruption

mechanisms. *Nature*, 277: 440-443.
Sparks, R. S. J. and G. P. L. Walker (1977) The significance of vitric-enriched air-fall ashes associated with crystal-enriched ignimbrite. *Journal of Volcanology and Geothermal Research*, 2: 329-341.
Thorarinsson, S. (1944) Tefrokronologiska studier pa Island. *Geografiska annaler*, 26: 1-217.
Walker, G. P. L. (1973) Explosive volcanic eruptions — a new classification scheme. *Geologische Rundschau*, 62: 431-446.
Walker, G. P. L. (1981) Plinian eruptions and their products. *Bulletin of Volcanology*, 44: 223-240.
Walker, G. P. L. and Croasdale, R. (1972) Characteristics of some basaltic pyroclastics. *Bulletin of Volcanology*, 35: 303-317.
White, J. D. L. and B. Houghton (2000) Surtseyan and related phreatomagmatic eruptions. *In*: H. Sigurdsson, B. Houghton, S. R. McNutt, H. Rymar and J. Stix (eds.), *Encyclopedia of Volcanoes*, Academic Press, San Diego, 495-511.
Wright, J. V., A. L. Smith and S. Self (1980) A working terminology of pyroclastic deposits. *Journal of Volcanology and Geothermal Research*, 8: 315-336.

(Received 30 November 2002, Accepted 20 December 2002)