

Crumbling of dacite dome lava and generation of pyroclastic flows at Unzen volcano

Hiroaki Sato*, Toshitsugu Fujii† & Setsuya Nakada‡

* Department of Natural Environmental Sciences, Faculty of Integrated Arts and Sciences, Hiroshima University, Hiroshima, 730 Japan

† Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, 113 Japan

‡ Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University, Hakozaki, Fukuoka, 812 Japan

RECENT modelling of volcanic eruptions has shown that the efficiency of subsurface degassing of magmas determines whether magma erupts explosively or effuses quietly^{1,2}. Slow uprise of magma is often accompanied by effective degassing, leading to the extrusion of lava flows and domes. Although lava dome extrusion is one of the less explosive modes of eruption, it is often accompanied by explosive pyroclastic activities³⁻⁵. The 1991 eruption of Unzen volcano provided an opportunity to observe at close range

several types of small-scale pyroclastic flow (glowing avalanches) originating from lava domes. Most of the pyroclastic flows are of Merapi type, caused by blocks falling from a collapsing dome; others are of Peléan type originating in an explosion from the side of a dome. The lavas apparently show variable degrees of self-explosivity. We suggest that variable degrees of degassing of the magma produced a wide range of excess pore pressures in the extruded lava domes, resulting in both Merapi-type and Peléan-type pyroclastic flows from the domes.

The extrusion of viscous lavas near the summit edge of the Fugendake dome of Unzen volcano, western Japan, began on 20 May 1991, and has been continuing at a rate of $1-3 \times 10^5 \text{ m}^3$ per day for more than a year⁶⁻⁸. About 4,000 small-scale pyroclastic flows from the domes have been recorded seismically in the first year. One of the largest pyroclastic flows, on 3 June 1991, killed 43 people including three volcanologists⁹.

Close examination of videotapes verifies that instantaneous explosive fragmentation of a falling block causes a Merapi-type pyroclastic flow. Figure 1 illustrates the mode of collapse of a block falling from the second lava dome on 8 August 1991. The falling block is ~70 m high. The pyroclastic flow that accompanied this collapse was one of the smallest of the eruption, with a tremor lasting only 30 s, and was also the least explosive.

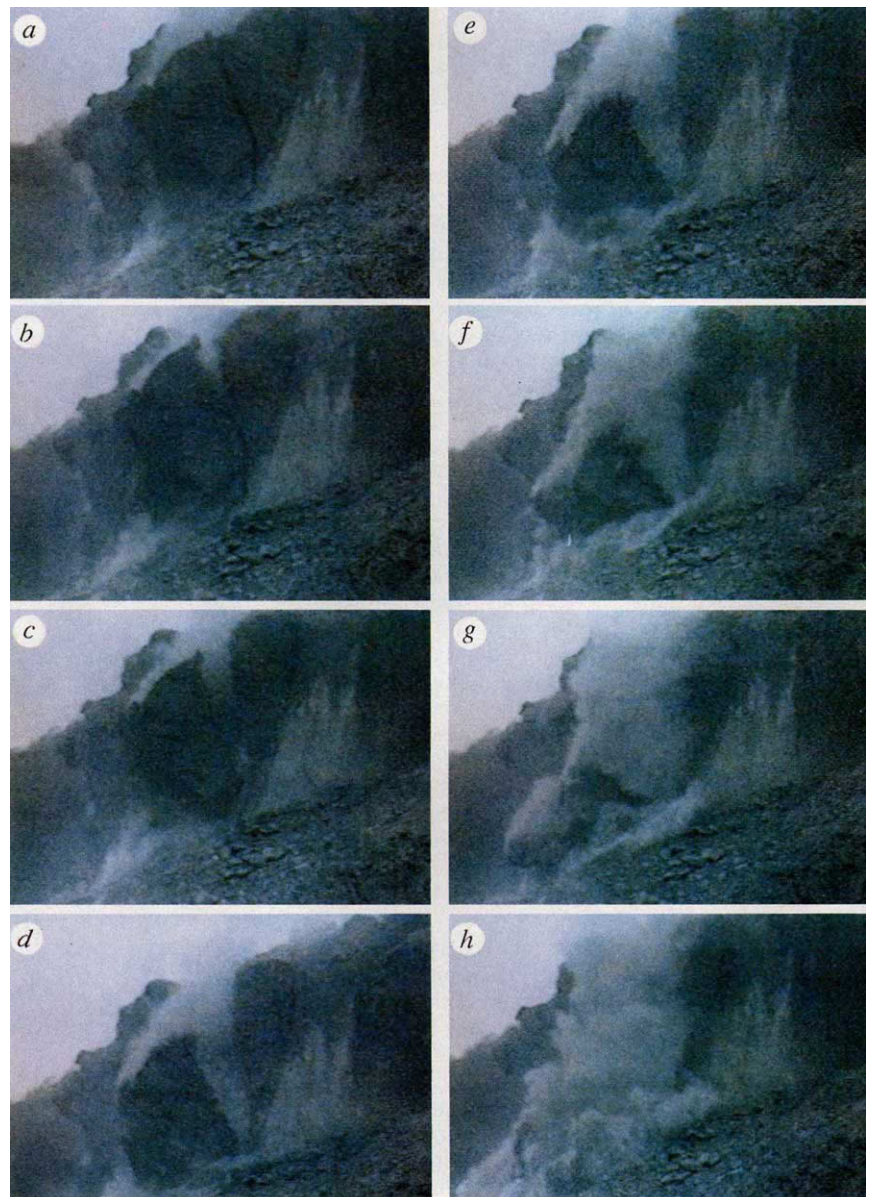


FIG. 1 Mode of crumbling of a lava block at the front of the second lava dome of Unzen volcano, at 16:17 on 8 August 1991. The block is ~70 m high. The photograph is copied from a videotape (NHK Japan) obtained ~5 km northeast of the lava dome. Frames are at 1-s intervals.

Ash-charged gas is issued from the surface of the block as soon as it begins to fall, then the block crumbles from below by explosive fragmentation. The trigger for fragmentation may be unloading¹⁰ or landing shock, or both. The process resembles the explosive demolition of a building. Similar but less definitive pictures were obtained during the 1980–86 eruption of Mount St Helens¹⁰, which involved dome building and collapse. The process implies that the falling block has low tensile strength, and some internal pore-gas pressure.

Self *et al.*¹¹ suggested that the likely range of tensile strength of andesite at subsolidus temperature is 100–200 bar. Dacite lava from the 1991 Unzen eruption, however, is highly viscous and contains 30–40 vol% vesicles, so it may have lower tensile strength. The lava samples generally consist of 30–50 vol% of crystals (phenocrysts and microlites) and glass. Lower tensile strength could be caused by high strain in viscous melt due to flow of the lava and presence of crystals. The matrix glass is rhyolitic in composition, and the viscosity (calculated after the method of Shaw¹²) is 10^{12} poise (water-free) to 10^9 poise (for 2 wt% of water) at 800 °C. Although we do not have experimental data on the tensile strength of the lava, field examination of hot blocks indicated it to be low: striking a block in a pyroclastic flow deposit with a hammer shattered it into fine particles. A similar observation was made at Mount St Helens¹⁰.

The explosive degassing of the lava blocks suggests that the dome lava contained high-pressure pore gas. The high concentration of volatiles in silicic domes leading to explosive collapse was proposed by Rose *et al.*³ and amplified by Fink *et al.*^{5,8,13}. The water content in the matrix glass may indicate the pore-gas pressure. Maeda *et al.*¹⁴ reported bulk-rock H₂O(+) contents for the lava blocks in the range 0.18–0.46 wt%. Estimating the water content of the matrix glass is difficult because of uncertainty about the water content of matrix pargasite. The H₂O content of the bulk matrix is calculated to be 0.10–0.45 wt%, corresponding to an equilibrium saturation pressure of ~1–13 bar. These are probably only minimal values of the pore pressure of the dome lavas, because the analyses were made on lava blocks in pyroclastic flows, possibly the least explosive part of the dome lava, and because water could be degassed after the fragmentation.

High pore-gas pressure is suggested by the explosive growth of the ash clouds arising from pyroclastic flows. Air entrainment¹⁵ apparently did not take place near the front of these pyroclastic flows. Rather, the ash-charged clouds expanded upwards and forwards from the base of the advancing front of pyroclastic flows. This observation suggests that shearing at the bottom of the pyroclastic flow breaks large blocks into fine particles, where high-pressure pore gas is liberated and expands, charged with ash. The thickness of the cloud varies from one pyroclastic flow to another. Pyroclastic flows generated from new lava blocks near the vent are much more explosive and have thick billowing clouds, whereas those from the lava front at some distance from the source vent (Fig. 1) are generally less explosive. Because of its high viscosity, the lava resists the expansive force of bubbles during depressurization, so it is likely that the lavas just extruded from the vent have excess pore pressure (over hydrostatic pressure). Sparks¹⁶ simulated bubble formation numerically, and pointed out that viscosities of the order of 10^8 poise can cause excess pore pressures of several tens of bars. The apparent extrusion rate (several tens of metres per day) and high viscosity ($5\text{--}13 \times 10^{10}$ poise)¹⁷ suggest that the lavas just extruded could have excess pore pressures of tens of bars if degassing of water can be neglected. The excess pore pressure may decrease towards the surface of the lava because of cooling, and because jointing and fracturing of the lava surface caused by flow release the inner gas. Pyroclastic flows are often preceded by non-explosive block falls. Possibly, a fall of cool surface blocks is followed by explosive collapse of inner hot lavas to generate pyroclastic flows.

The mode of eruption of pyroclastic flows from lava domes,

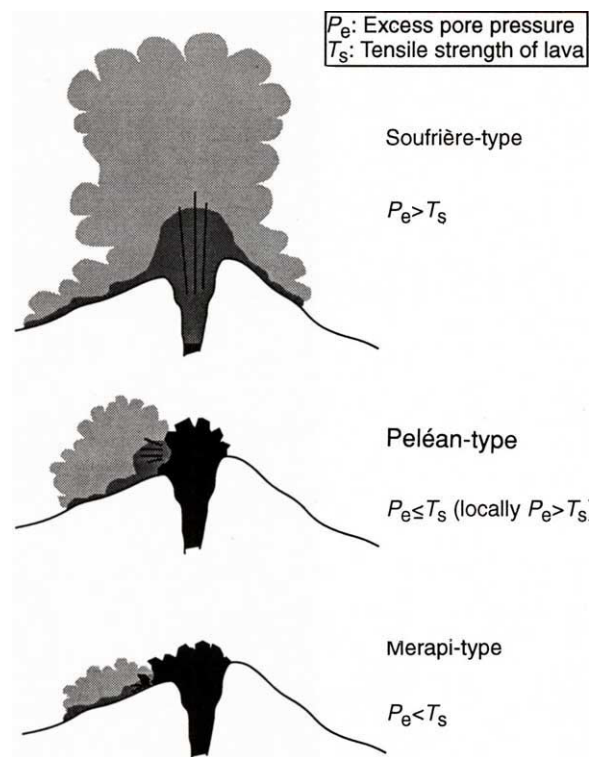


FIG. 2 Model of generation of pyroclastic flows in terms of excess pore pressure and tensile strength of lavas. Black area, massive lava; densely dotted area, densely charged pyroclastics and block and ash flows; lightly dotted area, ash-charged cloud.

in this case mainly Peléan and Merapi types, can be interpreted in terms of the relationship between tensile strength and excess pore pressure of lavas (Fig. 2). If the tensile strength of dome lava exceeds the excess pore pressure, the dome does not disintegrate unless a block fall triggers fragmentation. On the other hand, lateral explosion in the Peléan-type pyroclastic flow is generated where a part of the extruded dome lava has pore pressure greater than the tensile strength of the lava. Extruded dome lava is probably heterogeneous in water content and excess pore pressure (water distribution in the Mount St Helens dome was heterogeneous¹⁸). The initial water content of the 1991 Unzen lava is estimated from high-pressure phase equilibrium studies¹⁹ to be more than 4 wt%. The dome lava lost most of this water before reaching the surface. Details of the degassing mechanisms of viscous lavas are controversial^{2,13,20}, but it is conceivable that forced flow of the lava in the conduit makes cracks between pores in the lava, which may subsequently be annealed, but give some gas permeability. This is similar to percolation processes, which often show fractal size distribution. If the lava is similarly degassed by channelling of the pores, the water in the lava may be heterogeneously distributed. The pore size in bread-crust bombs ejected in the 11 June 1991 Vulcanian explosion of the Unzen lava dome ranges from less than $10 \mu\text{m}$ up to tens of centimetres, with no characteristic size. The bombs also show heterogeneous porosity distribution. Therefore, excess pore pressure is irregularly distributed in the extruded dome lavas, and Peléan-type pyroclastic flow may occur where excess pore pressure of the newly extruded lava locally exceeds the tensile strength of the lava.

If all of the dome lava had excess pore pressure greater than the tensile strength, the dome would explode instantaneously; this may correspond either to a Vulcanian-type explosion or a Soufrière- (or St Vincent-) type pyroclastic flow eruption^{21,22} (Fig. 2). During the 1991–92 eruption of Unzen volcano, Vulcanian-type explosions took place on 8 June and again on 11

June 1991. The 8 June event was preceded by seven Merapi-type and Peléan-type pyroclastic flows, which removed the capping dome of the lava conduit. Rapid removal of the cap released the pressure of the underlying water-rich magmas, which had higher excess pore pressure, causing an explosive eruption.

We thus attribute variations in the mode of eruption of this one lava dome, from Vulcanian-type explosion through pyroclastic flows to non-explosive rock fall avalanche, to variable excess pore pressures in the lavas. The extruded lava, although its major element composition has remained nearly constant for more than a year ($\text{SiO}_2 = 65 \text{ wt}\% \pm 0.5 \text{ wt}\%$), may have heterogeneous excess pore pressure due mainly to percolative degassing in the conduit. □

Received 29 June; accepted 27 October 1992.

1. Jaupart, C. & Allegre, C. J. *Earth planet. Sci. Lett.* **102**, 413–429 (1991).
2. Eichelberger, J. C., Carrigan, C. R., Westrich, H. R. & Price, R. H. *Nature* **323**, 598–602 (1986).

Exact tracking of pollen transfer and mating in plants

L. Anders Nilsson*, Elisabeth Rabakonandrianina† & Börge Pettersson*

* Department of Systematic Botany, Villavägen 6, S-752 36 Uppsala, Sweden

† Service de Biologie Végétale et Biochimie, Université d'Antananarivo, BP 906, Antananarivo 101, Madagascar

UNLIKE animals, where individuals engage in direct sexual encounters, higher plants interact sexually only through minute, usually animal-mediated pollen grains, a trait that has hampered understanding of processes that govern plant evolution. A new technique using microtags to mark individual orchid pollinia and monitoring of all stigmas for pollination made it possible to measure exactly pollen transfer and mating pattern in a plant species. We report here that in populations of a hawkmoth-pollinated orchid, *Aerangis ellisii*, pollen transfers were found to be infrequent, to involve single pollen parents, and to occur mostly within 5 metres. Pollinator-mediated patterns of disproportional reproductive success suggest that floral traits are being shaped by mutual sexual selection as proposed by Darwin^{1–3}. The microtag method opens an avenue for novel exploration of plant evolution.

Use of coloured dye particles as pollen analogues has yielded components of fitness for selected plant individuals⁴, whereas for favourable cases genetic paternity-exclusion procedures^{5–7} have allowed pollen parents to be identified for up to 85% of the fruits produced⁸. But the genetic techniques have not permitted the complete mapping and analysis of animal-mediated pollen transfer, effectuated matings and amount of gene flow in whole natural populations. Orchids package their pollen in coherent masses, the pollinia, which are often dispensed intact to stigmas by the pollinator. Orchid pollinia are often solid, 1–2 mm in diameter and only two per flower. Marking pollinia with coloured histochemicals has allowed the study of gene flow between a few individuals within populations⁹. An isolated group of populations of *Aerangis ellisii* (Orchidaceae) in Madagascar was studied throughout its bloom in 1992 (Table 1). A plant produces one to several inflorescences, each with 8–12 white, long-spurred flowers; pollination is by hawkmoths¹⁰. All pollinia in two populations, A and D (containing 148 and 3 flowering individuals, respectively), were marked with microtags. Two control populations, B and C, were also studied.

Monitoring of stigmas revealed the hawkmoth-generated pattern of pollinium transfers (Fig. 1), where a transfer involved one or two donor pollinia being captured by a flower's stigma

3. Rose, W. I., Pearson, T. & Bonis, S. *Bull. Volcanol.* **40**, 23–38 (1977).
4. Fink, J. H. & Manley, C. R. *IAVCEI Proc. Volcanol.* **1**, 169–179 (1989).
5. Fink, J. H. *Nature* **351**, 611 (1991).
6. Ohta, K. *J. geol. Soc. Japan* **97**(7), i–iii (1991).
7. Nakada, S. & Fujii, T. *J. Volcanol. geotherm. Res.* (in the press).
8. Fink, J. H. *Nature* **357**, 119 (1992).
9. Shimozuru, D. *Nature* **353**, 295–296 (1991).
10. Mellors, R. A., Waitt, R. B. & Swanson, D. A. *Bull. Volcanol.* **50**, 14–25 (1988).
11. Self, S., Wilson, L. & Nairn, I. A. *Nature* **277**, 440–443 (1979).
12. Shaw, H. R. *Am. J. Sci.* **272**, 870–893 (1972).
13. Fink, J. H., Anderson, S. W. & Manley, C. R. *J. geophys. Res.* **97**, 9073–9083 (1992).
14. Maeda, S. *et al. Abstr. Fall Mtg. Volcanol. Soc. Japan* **2**, 62 (1991).
15. Wilson, C. J. N. *J. Volcanol. geotherm. Res.* **8**, 231–249 (1980).
16. Sparks, R. S. J. *J. Volcanol. geotherm. Res.* **3**, 1–37 (1978).
17. Seino, M., Fukui, K., Uihira, K., Hashimoto, T. & Yamasato, H. *Abstr. Fall Mtg. Volcanol. Soc. Japan* **2**, 39 (1991).
18. Anderson, S. W. & Fink, J. H. *Nature* **341**, 521–523 (1989).
19. Tomiya, A., Takahashi, E. & Nakada, S. *Abstr. 1992 Japan Earth planet. Sci. Joint Mtg.* 166 (1992).
20. Fink, J. H. *Nature* **352**, 188 (1991).
21. Macdonald, G. A. *Volcanoes* (Prentice-Hall, Englewood Cliffs, New Jersey, 1972).
22. Fisher, R. V. & Schmincke, H.-U. *Pyroclastic Rocks*, 472 (Springer, Berlin, 1984).

ACKNOWLEDGEMENTS. We thank K. Ohta and K. Kamo for their support at Unzen. Comments by D. Swanson, R. S. J. Sparks and J. Fink improved the manuscript. Figure 1 is from a videotape offered by NHK Japan.

(Fig. 2). Transfers were few in all populations (Table 1). In populations A and D, 37% and 67% of the transfers, respectively, involved untagged pollinia representing foreign, imported gene flow. There were no transfers between populations A and D, nor from them to either B or C.

Pollinium dispersal was mostly between adjacent plants (<5 m apart), but 26% travelled >15 m; maximum transfer

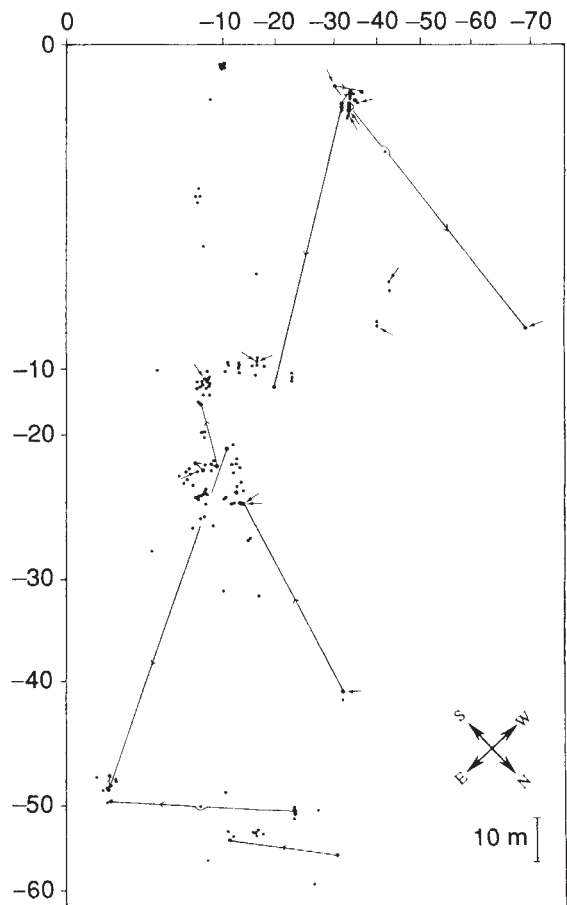


FIG. 1 Pattern of pollinium transfer within the experimental population A of *Aerangis ellisii* growing near the top of Ambatolava rock. Each dot represents an individual plant, and the lines connect plants that participated in tagged transfers. Solitary arrows denote receipt of untagged pollinia (foreign, imported gene flow). Relative altitude (in m) is indicated along the margins. A few plants (without transfers) that occurred further down the rock have been omitted from the figure.