Glowing Avalanches: New Research on Volcanic Density Currents

Greg A. Valentine and Richard V. Fisher

Explosively produced volcanic density currents (gravity flows) have been problematic ever since horizontally moving nuées ardentes (glowing clouds) were first described from the 1902 Mont Pelée eruption that killed 28,000 people on Martinique in the Lesser Antilles. Over the past three decades, research has intensified on volcanic gravity flows and how their materials become deposited. The gravity flows are made of volcanic particles (pyroclasts) and vapor forming a mixture that is denser than air and therefore flows along the ground, being channeled into depressions to varying degrees. The complexity of these flows is intriguing not only from a geologic viewpoint, but also from a fluid dynamic perspective. High flow speeds, very high temperatures, external shrouds of volcanic ash, and unpredictability all combine to make direct observation of these currents nearly impossible with existing techniques. Our understanding of pyroclastic currents thus relies on indirect approaches such as experimental and theoretical modeling and, most importantly, field observations of deposits left by the flows—the "ground truth."

Fast and hot. A pyroclastic flow produced during an eruption of Mount St. Helens on 7 August 1980. Hot ash and gas erupted from the vent, located in the center of the photograph, and flowed down the north flank of the volcano. Such flows have temperatures approaching 1000°C and can move with speeds of up to 300 m s^{-1}. The photograph was taken 11 km north of the volcano, looking south. [Courtesy Richard P.

Previous field studies have suggested that some types of volcanic deposits (called ignimbrites, which are massive and poorly sorted as described below) are deposits from gravity flows with high particle concentration having rheological characteristics similar to debris flows but with high mobility owing to fluidization from upward-moving vapors. Recent research (*1–4*) suggests that this widely accepted view of ignimbrite formation needs to be reassessed. For example, Branney and Kokelaar (*1*) have pointed out that it is possible that fragments within the transport system are suspended by turbulence during most of the runout distance, but following rapid accumulation of particles and development of a still-moving, high-density underlayer (the depositional system), movement is nonturbulent within the last few moments of flow. The structures within the deposit record these last few moments of en masse flow.

The collapse of vertical eruption columns to form pyroclastic flows was recognized during the 1929 eruption of Komagatake, Japan (*5*), and was postulated from sedimentological data at St. Vincent, British West Indies (*6*). Using observations of the development of a base surge from a 1947 nuclear explosion at Bikini Atoll (South Pacific) as a model, one of us (R.V.F.) suggested column collapse (also called "bulk subsidence") as a cause of pyroclastic flows leading to development of ignimbrites (*7*), and the process of column collapse was described from a series of photographs showing the development of a surge at Capelinhos (Azores) (*8*). The connection between column collapse and the origin of pyroclastic flow and surge deposits was quantitatively established in the 1970s (*9, 10*). Most pyroclastic gravity flows are formed by this column collapse mechanism whereby a jet of pyroclasts and gas is ejected from a volcanic vent, rises until its initial kinetic energy is spent, and then falls back to the ground because the mixture is more dense than the surrounding atmosphere (analogous to a fountain); when the mixture impacts the ground it flows outward, forming gravity currents that move over the landscape under their own momentum (*10, 11*). In the case of the 18 May 1980 blast at Mount St. Helens, Washington, material was ejected laterally over the ground as the magma decompressed. The flow initially accelerated, but as the material traveled away from the vent, velocity decreased to the point where gravitational forces became dominant over inertial forces and the flow transformed to a gravity current (*12*). In some cases shock waves from volcanic explosions may trigger the currents (*13*). A fourth mechanism for generating pyroclastic gravity currents is collapse of steep fronts of viscous lava domes and flows (*14*), as recently occurred at Unzen volcano, Japan (*15*). The currents have velocities that range as high as 300 m s^{-1} based on model calculations and the height of topography surmounted by the flows (*12, 16*) and can travel distances in excess of 100 km from their source vents, carrying pyroclasts ranging in size from micrometers to meters at temperatures as high as 1000°C.

The deposits of pyroclastic gravity flows have a wide spectrum of characteristics. At one end of the spectrum are sequences of thin beds, each on the order of 1 cm in thickness, that can form as dunes and can be cross-stratified. These are commonly termed "pyroclastic surge" deposits, the name "surge" being originally derived from turbulent base surges derived from nuclear explosions (the base surge is a ring of debris that flows outward from the base of rising mushroom clouds from the explosions). Volcanic base surges were first recognized at Mount Taal Volcano in the Philippines (*17*). At the other end of the spectrum is a type of deposit called "ignimbrite." Ignimbrites are relatively structureless (compared to pyroclastic surge deposits) and are composed chiefly of small, sand and silt size pyroclasts, forming a matrix within which larger fragments are supported.

Although ignimbrites are relatively structureless, they display some subtle sedimentological features that have been key in interpretative studies (*18, 19*). Large fragments tend to be absent in the basal portion of the deposits (typically 10 to 100 cm thick). Above this basal zone large, dense fragments are concentrated low in the deposits whereas large, low-density fragments are concentrated near the tops. These are common features of debris flows, where particles are so highly concentrated (between 0.1 and 0.6 volume fraction) that the mixture behaves in a manner similar to Bingham plastics (materials that have a linear relationship between shear stress and strain above a finite yield stress). Such flows form deposits by en masse frictional "freezing" as stress drops below the yield stress value. At first glance it would seem that such flows would not be very mobile, but it was thought that vapors being released by the pyroclasts during the flow would suspend (fluidize) the fine-grained matrix, thereby allowing large run-out distances. This ignimbrite depositional model differed markedly from the common model for pyroclastic surges, which as-

G. A. Valentine is in the Geoanalysis Group, MS F665, Los Alamos National Laboratory, Los Alamos, NM 87545. R. V. Fisher is in the Department of Geological Sciences, University of California, Santa Barbara, CA 93106.

sumed, partly on the basis of the presence of bedforms such as dunes, that surges are highly unsteady, turbulent currents with a low concentration of particles that are carried by turbulent suspension (similar in some ways to sand storms). It was thought that pyroclastic currents could carry particles either by turbulent suspension as surges or, if turbulence intensity was insufficient to suspend the particle load, by concentrated, partly fluidized pyroclastic flows (producing ignimbrites).

This view of ignimbrite emplacement satisfied many common observations of ignimbrites around the world, but some nagging problems remained. For example, observations of the 1902 Mont Pelée eruption indicated that turbulent suspension of particles in a relatively dilute mixture was the dominant transport mechanism (*20*). The flows at Mont Pelée were density-stratified (*21, 22*) so that lower, denser portions were strongly diverted by topography whereas higher, less dense portions were not. Many ignimbrites display compositional variations that represent variations in the source magma. For the en masse deposition model, in simplistic terms, the compositions from the early part of the eruption would be at the far end of the deposit whereas late-erupted material would be near the vent, and at a given location there would be little or no vertical compositional variation. However, vertical variations have been observed within deposits even though sedimentologically they appear to have been deposited en masse (*7, 23*). Some ignimbrites, especially those emplaced at high temperatures, show textural evidence of deposition from the ground up (*24*) instead of frictional "freezing" of the whole flow, thereby returning to an idea proposed in 1966 (*7*). Furthermore, Druitt's exciting study (*4*) of deposits left by the 18 May 1980 blast at Mount St. Helens showed that within a single deposit there is a gradual transition from typical ignimbrite characteristics in areas proximal to the vent to those of typical pyroclastic surge deposits near the distal margins. This observation stands in contrast with the view that pyroclastic currents travel either as dense, partly fluidized flows or as turbulent suspensions, suggesting that there must be a mechanism which can produce a spectrum of flow behaviors and deposit types.

Two recent papers (*2, 3*) suggest other reasons why the model of dense, partly fluidized, nonturbulent pyroclastic flows may need reassessment. Hayashi and Self (*2*) compared the mobility of ignimbrite-producing flows to debris avalanches of both nonvolcanic and volcanic origins and found that pyroclastic flows and avalanches have similar mobilities. Because fluidization probably does not play a major role in the movement of avalanches, it now seems that there is no compelling reason to invoke it for pyroclastic flows (note that ignimbrites do show ample evidence for partial fluidization after deposition, when vapors escape from the compacting deposits). Anilkumar, Sparks, and Sturtevant (*3*) carried out experiments on the rapid acceleration of gas heavily laden with particles and found that both velocity and particle concentration exhibit large, rapid fluctuations in the resulting flows. These experiments, combined with unsteadiness in the "mean" flow [as shown in numerical simulations (*25*)], strongly suggest that previous models of pyroclastic flows were much too simple.

How can sedimentological evidence for dense flow and en masse deposition be reconciled with compositional, textural, and theoretical evidence that ignimbrites are emplaced by highly turbulent flows that deposit from the bottom up? Branney and Kokelaar (*1*) have drawn on the growing body of ignimbrite studies and from the sedimentology literature to form a picture of pyroclastic flow and deposition that seems to accommodate these seemingly conflicting observations. They apply the distinction between the transport system of a pyroclastic flow, which carries particles most of the distance from the vent to near their point of deposition, and its depositional system (*26*). The depositional system forms the lowest part of the flow, has a higher density than the main flow, and is capable of flowing for relatively short distances during which it may be diverted by topography (*22*). Branney and Kokelaar discuss how rapid sedimentation from the transport system will cause local thin, massive flow in the depositional system. After possibly flowing for short distances (compared to the regional scale of flow) the depositional system freezes due to fluctuations in the overriding flow, to be subsequently buried by a similar bed. The amount of structure (layering, for instance) in an ignimbrite then is related to the degree of unsteadiness in the overall flow system. Steady flow will produce a single massive layer, but one that was built from the bottom up, thereby accounting for observed compositional variations. The ideas of Druitt (*4*), based on the Mount St. Helens deposits, mesh well with the model of Branney and Kokelaar.

There is still considerable disagreement on the problem of mobility of gravity flows. The answer to the disagreement may lie in areas where the flows have surmounted high mountain ranges and have crossed bodies of water (*27*) and may go far to unravel fundamental questions about hydrodynamic characteristics of pyroclastic gravity flows. One hypothesis is that pyroclastic flows surmount high topographic barriers because they are in an expanded state, higher than the topographic relief (*26, 28*). The second prevalent hypothesis is that they are primarily nonturbulent, high-density flows that surmount high barriers because of their momentum (*10, 29*). Variations in the deposit characteristics over very high terrain should provide some important clues as to which model is more appropriate.

One of the most intriguing aspects of pyroclastic flows relates to the insight that they might provide for an important class of fluid dynamics, that is, high-speed multiphase flows. Although pyroclastic flows are difficult to observe directly, they may be the closest that we can come to adequate "experiments" of fast multiphase flows where gravitational forces cannot be neglected. One outstanding problem is the nature of turbulence in flows with large density variations and high Mach numbers. Ignimbrites can be viewed as the end results of natural experiments of such flows. The challenge is to determine the initial and boundary conditions for the "experiments" and then to deduce the physics of the flows. This is somewhat backward compared with the usual physics and engineering approaches of carefully setting the initial and boundary conditions and then watching the outcome. By combining geologic observation and intuition with fluid dynamic theory, ignimbrite studies have the potential of contributing to several disciplines.

References

1 M J. Branney and P Kokelaar, *Bull. Volcanol.* **54**, 504 (1992).
2. J N Hayashi and S. J Self, *J. Geophys. Res* **97**, 9063 (1992).
3. A. V Anilkumar, R. S. J Sparks, B. Sturtevant, *J. Volcanol. Geotherm. Res.*, in press
4. T. H Druitt, *Bull. Volcanol.* **54**, 554 (1992).
5. S. Kozu , *Tschermaks Mineral Petrorg Mitt.* **45**, 133 (1934)
6. R. L. Hay, *J. Geol.* **67**, 540 (1959).
7. R. V. Fisher, *Am. J. Sci.* **264**, 350 (1966).
8. A C. Waters and R. V. Fisher, *J. Geophys. Res.* **76**, 5596 (1971).
9. R. S. J. Sparks and L. Wilson, *J Geol. Soc London* **132**, 441 (1976).
10. ———, G. Hulme, *J. Geophys. Res.* **83**, 1727 (1978).
11. G. A. Valentine and K. H. Wohletz, *ibid.* **94**, 1867 (1989).
12. S. W. Kieffer, *U.S. Geol. Soc. Prof. Pap. 1250* (1981), p. 379.
13. K. H. Wohletz, T. R. McGetchin, M. T. Sandford II, E M. Jones, *J. Geophys. Res.* **78**, 8269 (1984).
14. R. A. Mellors, R. B. Waitt, D. A. Swanson, *Bull. Volcanol* **50**, 14 (1988).
15. H. Sato, T. Fujii, S. Nakada, *Nature* **360**, 664 (1992).
16. C. J. N. Wilson, *Philos. Trans. R. Soc. London A* **314**, 229 (1985).
17. J G. Moore, *Bull Volcanol.* **30**, 337 (1967).
18. R. S. J. Sparks, S Self, G. P L. Walker, *Geology* **1**, 115 (1973).
19. C. J. N. Wilson, *J. Volcanol. Geotherm. Res.* **8**, 231 (1980).
20 R. L. Smith, *Geol. Soc. Am Bull.* **71**, 795 (1960)
21. R. V Fisher and G. Heiken, *J Volcanol. Geotherm. Res.* **13**, 339 (1981).
22. G. A. Valentine, *Bull. Volcanol.* **49**, 616 (1987).
23 J. V. Wright and G. P. L Walker, *J. Volcanol Geotherm. Res.* **9**, 111 (1981).
24. C. E Chapin and G R. Lowell, *Geol Soc Am. Spec Pap. 180* (1979), p. 137
25. G. A. Valentine and K H. Wohletz, *Geology* **17**, 641 (1989).
26. R. V. Fisher, *Geol Soc. Am. Bull.* **102**, 1038 (1990)
27 ———, G. Orsi, M Ort, G. Heiken, *J. Volcanol. Geotherm Res.*, in press.
28 S. Yokoyama, *Sci Rep. Tokyo Kyoiku Daigaku Sect C* **12**, 17 (1974).
29. T. P Miller and R. L. Smith, *Geology* **5**, 173 (1977).