Volcanic Dilemma: Flow or Blow?

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One of the most spectacular displays of nature is the eruptive behavior of active volcanoes. At one end of the spectrum of eruption styles is the slow effusive extrusion of viscous, high-silica lavas, like some of the volcanic flows in Iceland. At the opposite extreme is the catastrophic, explosive ejection of fragments, like the classic eruptions of Vesuvius or Mount St. Helens. Both kinds of behavior may even occur within a single volcanic center. The eruptive style of such volcanoes determines the danger to human life, property, and the environment posed by volcanism on our planet. Behind these events lies the physical and chemical nature of the magma. Recently, experiments and numerical simulations of explosive volcanism have implicated a seemingly paradoxical event involving solidlike behavior of liquids—the glass transition—in generating brittle failure of melts in volcanoes.

Because volcanism and its associated magmatic processes provide such a remarkably wide range of conditions for the behavior of silicate melts, it is no surprise that much of the recent investigation has been performed by experimental geoscientists (geochemists, petrologists, and geophysicists). A great deal of attention has been focused on the rheology and mechanical properties of melts and magmas (that is, melts plus crystals plus bubbles), which relate the stresses driving eruptive behavior to the nature and extent of the resulting strain. For the past 5 years, a central concern has been the role of the brittle-ductile or glass transition in volcanological processes (see figure).

Textural evidence for the brittle failure of highly viscous magmas has been compiled over the years by microscopic examination of the fragmented products of explosive eruptions (*1*). In 1989, a quantification of the conditions thought to be necessary for the generation of a brittle response of silicate melts was proposed (*2*). The essence of that argument was that the strain rates of deformation of the magma must be sufficiently high to drive the melt phase into a non-Newtonian, shear-thinning phase that is terminated by brittle failure. The onset of non-Newtonian rheology turns out to be easily predictable from a scaling to the Maxwell relation for linear viscoelasticity. As a result,

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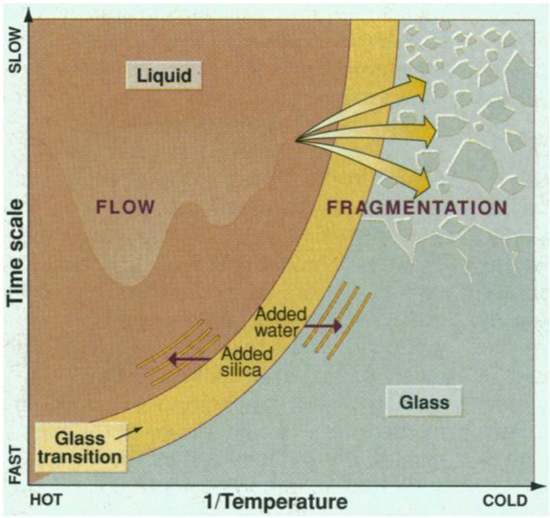

The glass transition in time–reciprocal temperature space. Deformations slower than the structural relaxation time generate a relaxed, viscous liquid response of the melt. When the time scale of deformation approaches that of the glass transition, the result is elastic storage of strain energy for low strains and shear thinning and brittle failure for high strains. The glass transition may be crossed many times during the formation of volcanic glasses. The first crossing may be the primary fragmentation event in explosive volcanism. Variations in water and silica contents can drastically shift the temperature at which the transition in mechanical behavior is experienced. Thus, magmatic differentiation and degassing are important processes influencing the melt's mechanical behavior during volcanic eruptions.

the strain rate required for failure can be predicted for the viscosities normally expected in hydrous rhyolites. Yet, the predicted strain rates are higher than those obtained from the ascent rates of magma in conduits. This yields the perplexing conclusion that the strain rates in nature are too low to drive ascending magma into the glass transition region, where brittle failure could occur. Recent studies, however, appear to offer a tantalizing solution to the seeming inconsistency provided by the apparent textural evidence for brittle failure on the one hand versus the inadequate strain rates involved in magma ascent to generate brittle failure on the other.

The first component is experimental. In the past 5 years, investigations into the behavior of low-temperature analog materials undergoing rapid deformation have been conducted. These analog materials comprise quite a menagerie of substances, including explosively reacting K_2CO_3 and HCl, gum rosin with added acetone, superheated freon liquids with suspended solid spheres, carbonated water, and porous solid material (plastiprin), which all to a greater or lesser extent approximate one or more aspects of magmatic systems (*3*). The justification for using such a variety of analogs is to increase the dynamic range of several properties as well as to operate at low temperatures where imaging by available facilities is feasible. The challenge for such studies is to ensure that all important scaling considerations have been optimized and all relevant material properties of the analogs are sufficiently similar to those of magma. The clear contribution of such studies is the exposition of phenomena that may then be debated for the case of magma.

To move beyond the limits of analog materials, experiments have recently been carried out on the rapid decompression of actual dome magma samples at the conditions of eruptions in nature (*4*). Magma has been loaded into a "fragmentation bomb," taken to magmatic pressure and temperature conditions, and rapidly decompressed by the rupture of a membrane. This procedure thoroughly fragmented the sample, a crystal- and bubble-rich dacitic rock from Mount St. Helens representing the cryptodome of the 18 May 1980 eruption. This experiment showed that magma can be fragmented by rapid decompression and that formation and coalescence of bubbles is not essential. Thus, we can expect fragmentation events at a much lower bubble density than previously assumed. The experiments also demonstrate that the fragmentation process is feasible at much lower temperatures than those normally assigned to volcanic eruptions, with important consequences for hazard assessment on volcanoes such as Unzen and Merapi.

The strain rates induced by the rapid decompression (*4*) are quite high, and brittle response of the dome magma is expected from the Maxwell relation. Can such strain rates be achieved in nature? The answer to the difficult question of estimating strain rates in volcanic eruptions may have been answered recently by numerical simulations of the ascent of magma in a conduit (*5*). These simulations have raised the important point that even at moderate bulk ascent rates, the actual decompression rate in the fragmentation interval of the conduit may be significantly enhanced to a high volume stress or pressure gradient in the degassing melt. Why? The addition of a water to rhyolite melt results in a drastic, nonlinear drop in the melt (or magma) viscosity. Conversely, the dehydration of the magma as a result of ascent-driven bubble formation in the melt phase generates a steep vertical gradient in the viscosity of the magma precisely where the growth of bubbles and possibly crystallites are also contributing to higher viscosity. The vertical gradient in volume viscosity translates into a steep vertical gradient in pressure, with the result that the ascent of magma, driven from below, passes through a filter zone of extreme decompression rates. Here fragmentation by brittle failure may well be feasible.

The higher deformation rates implied by the recent simulations help to close the gap between the strain rates necessary for brittle failure in silicate melts and those provided by physical models of the magma ascent process. Yet, the parameterization of the physical properties of magmas on which such simulations are based are incomplete at best. A recent reanalysis of the influence of water on the viscosity of an analog rhyolite demonstrated that the nonlinearity of the viscosity increase during dehydration is even more extreme than previously estimated (6). Degassing of the magma is thus likely to proceed more efficiently down to a critical water content of perhaps 0.2 to 0.4 weight %, but then the magma would hit the catastrophe of a skyrocketing viscosity value, which blocks further viscous growth of bubbles. This effect has been dubbed the "viscosity quench" (7). Such a scenario, based on improved viscosity data, is likely to be capable of explaining the widespread occurrence of rhyolitic glass with water contents of a few tenths of a weight percent.

How much of the fragmentation in volcanic eruptions can be explained by brittle failure? For dome collapse and landslide-induced eruptions, brittle failure appears to be likely. For centrally fed eruptions, the debate currently rages. This vital issue is likely to generate considerable discussion and stimulate theoretical and experimental advances in volcanology and petrology in the next few years.

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An Excellent Lightness

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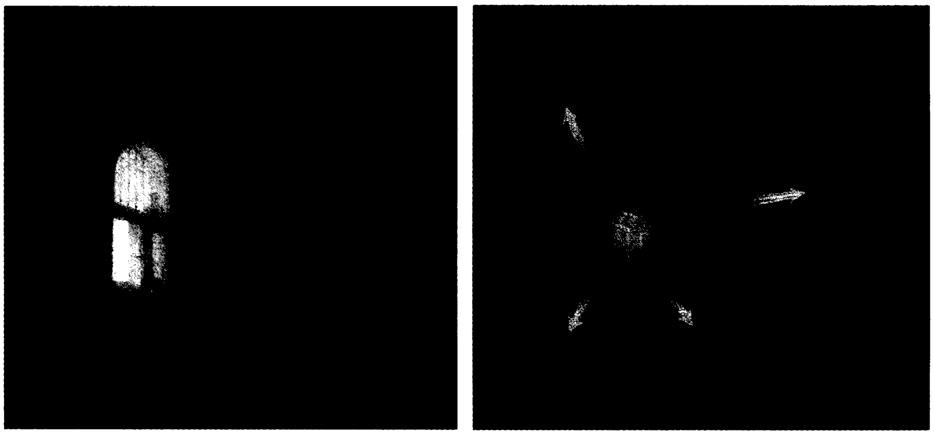
For many centuries before the present one, much of Western art aspired to high-fidelity reproduction of the world as it is naturally seen. Achieving visual equivalence or trompe l'oeil presents numerous technical challenges, the resolution of which became a major preoccupation for Renaissance artists such as Leonardo da Vinci. Notable among these challenges is that the range of light intensities one experiences when viewing an ordinary natural scene vastly exceeds—typically by some orders of magnitude—the range that can be brought forth by applying paint to canvas. A variety of tricks or illusions known collectively as chiaroscuro (literally, light-dark), which are now standard elements of the painter's trade, were developed to exploit the play of pigment in an effort to deceive the eye. These chiaroscuro effects are detailed in Leonardo's *Treatise on Painting* (*1*) and are among the earliest recorded insights into the nature of visual perception. The report by Rossi *et al.* (*2*) in this issue of *Science* sheds new light on the neural events that underlie one of most striking of chiaroscuro effects—a phenomenon known today as brightness induction (*3*). In doing so it brings us closer to understanding how the brain encodes the properties of surfaces in our visual environment.



(Left) ***Philosopher in Meditation,*** Rembrandt, 1632 (Louvre, Paris). Rembrandt was a master of chiaroscuro, using it to bring about illusory expansion of the range of light in the image, a phenomenon known today as brightness induction. (By viewing through a small aperture, one can see that the lighted window is very much darker than the page upon which it is printed.) **(Right) Reciprocal connections between neurons representing different regions of visual space are thought to contribute to brightness induction.** Reciprocal connection strength (indicated schematically by arrow width) is determined by local light intensity, such that the net activity of neurons representing areal brightness is influenced by spatial contrast.

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In his tutorial *Treatise*, Leonardo noted that "if you wish to produce an excellent darkness, give it an excellent lightness by way of contrast" (*1*, p. 84). In these simple words of advice to the aspiring painter, Leonardo captured what is now known to be an essential principle of visual perception: that perceived intensity of light (brightness) is not informed solely by the physical intensity of light (luminance) at a given point in space, but rather is determined largely by the contrast between the luminance at that point and the luminance of surrounding regions. By setting up contrast through adjacency of light and dark paints, Leonardo effected an illusory expansion of the range of light intensities perceived from the pigments. This illusion of induced brightness, which can be seen on page 1104 of this issue (Fig. 1A of Rossi *et al.*), is striking, and its use is pervasive in Western painting of the last 500 years.

The phenomenon began to attract the interest of vision scientists in the 19th century, when it became a focal point for debates as to whether sensory information is processed in a direct or a relational manner. The Austrian physicist Ernst Mach (*4*) was among the first to suggest a specific and detailed mechanism to account for brightness induction, which he thought involved "reciprocal action of neighboring areas of the retina" (p. 267) representing different areas of visual space (see figure). Mach's proposal was