Explosive caldera-forming eruptions and debris-filled vents: Gargle dynamics

Greg A. Valentine* and Meredith A. Cole
Department of Geology, University at Buffalo, 126 Cooke Hall, Buffalo, New York 14260, USA

ABSTRACT

Large explosive volcanic eruptions are commonly associated with caldera subsidence and ignimbrites deposited by pyroclastic currents. Volumes and thicknesses of intracaldera and outflow ignimbrites at 76 explosive calderas around the world indicate that subsidence is commonly simultaneous with eruption, such that large proportions of the pyroclastic currents are trapped within the developing basins. As a result, much of an eruption must penetrate its own deposits, a process that also occurs in large, debris-filled vent structures even in the absence of caldera formation and that has been termed “gargling eruption.” Numerical modeling of the resulting dynamics shows that the interaction of preexisting deposits (fill) with an erupting (juvenile) mixture causes a dense shear of fill material to be lifted along the margins of the erupting jet. This can cause an eruption that would otherwise produce a buoyant plume and fallout deposits to instead form pyroclastic currents as the dense sheath drives pulsing jet behavior. Increasing thickness of fill amplifies the time variation in jet height. Increasing the fill grain size relative to that of the juvenile particles can result in a much higher jet due to poorer mixing between the dense sheath and the dilute jet core. In all cases, material collapses along the entire height of the dense sheath rather than from the top of a simple fountain. These gargle dynamics provide strong backing for processes that have been inferred to result in intraplinian ignimbrites and simultaneous deposition from high- and low-energy pyroclastic currents.

INTRODUCTION

Large-volume, explosive volcanic eruptions eject tens to thousands of cubic kilometers of magma. Calderas—subidence features formed by rapid evacuation of large volumes of magma—are ubiquitous features of the larger eruptions. Studies of eroded calderas (e.g., Lipman, 2000) and drill cores in young examples (e.g., Nielson and Hulen, 1984) indicate that poorly sorted, pumice-rich deposits of pyroclastic currents (ignimbrites) within many calderas compose significant portions of the total volumes erupted (Fig. 1A; Item S1 in the Supplemental Material); the intracaldera deposits are normally significantly thicker than ignimbrites that flowed out of the calderas from the same eruptions (outflow; Fig. 1B). These data are consistent with pyroclastic currents having been partially trapped within progressively deepening calderas during eruption and imply that portions of the eruptions had to penetrate their own fresh deposits, a process referred to as “gargling eruption” by Wilson and Hildreth (1997). Eruptions that do not involve major caldera collapse may also have very wide, debris-filled vent structures through which continued eruption must penetrate (e.g., 1912 CE Novarupta vent in Alaska, USA; Hildreth and Fierstein, 2012).

We present numerical modeling that explores the effects of gargling on eruption dynamics. Although the simulations are greatly simplified compared to natural cases, they provide strong theoretical backing for processes that have been inferred from field studies and that have major effects on explosive eruptions and their deposits.

MODELING APPROACH AND RESULTS

We model the dynamics of eruption through particle layers with thicknesses between 50 and 100 m that represent freshly deposited caldera-fill ignimbrite or vent debris. Fluid flow is modeled with time-dependent, compressible-flow conservation equations solved for both gas and particles, which are coupled through momentum (drag) and heat exchange (as in Sweeney and Valentine, 2017; Valentine and Sweeney, 2018).

The same approach was used to study discrete phreatomagmatic explosions in debris-filled vents (Sweeney and Valentine, 2015; Sweeney et al., 2018), but here we focus on sustained discharges. The simplified two-dimensional (2-D), axisymmetric model domain extends to an altitude of 3 km (5640 m in one case) and radially away from the axis of symmetry to a horizontal distance of 6 km (Fig. 2). The 2-D approach does not account for the three-dimensional (3-D) structure of eddies that govern entrainment; simulated jet heights and transitions from dense jet to buoyant plume are therefore approximate but are expected to be reasonable (e.g., Nourazar and Safavi, 2017). Ambient air in the domain has density and temperature determined initially by the standard atmospheric profile (Sparks et al., 1997). The eruptive mixture of hot particles and H2O vapor enters the domain from the bottom boundary adjacent to the symmetry axis at a constant rate; these particles are referred to as juvenile particles. In all simulations, this inflow boundary (vent) has a 100 m radius.

The remainder of the bottom boundary has a no-slip condition while the top and right boundaries allow outflow. Caldera fill is represented by a bed of particles (porosity 40 vol%) that initially extends from the symmetry axis to the inner edge of a caldera rim; these preexisting particles are referred to as fill particles. The rim is simply represented as a rectangular obstacle of a defined height, located between 1000 and 1500 m from the axis. Although natural calderas have more complex 3-D topography and can erupt from vents with a range of sizes, shapes, and distances from developing caldera margins and which can be active individually or simultaneously, it is necessary to use our abstracted

*E-mail: gav4@buffalo.edu

1Supplemental Material. Item S1 (global caldera data), and Item S2 (modeling approach). Please visit https://doi.org/10.1130/GEOLO.S.14772804 to access the supplemental material, and contact editing@geosociety.org with any questions.

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Fig. 3B

mixture rise to a range of heights, and collapse the sheath; as a result, parcels of gas-particle larger upward speeds than on the outside of that are in direct contact with the jet gaining to material within the sheath, with parcels dense sheath or annulus of fill particles, which expands and accelerates in its margin as above, but the coarser particles also has an effect on jet dynamics (Fig. 2C). Collapse of a dense outer sheath contrasts with a simple fountain structure that results when a dense mixture erupts unimpeded into air, where material collapses from the top of a fountain via a stem structure that impacts the ground some distance from the jet (Fig. 2B inset; Valentine et al., 1992; Neri et al., 2003). A buoyant gas-particle mixture rises from the top of the currents and along the outer part of the complex jet structure. Thus, the presence of a relatively thin (50 m) intracaldera deposit can cause pyroclastic currents in an eruption that would otherwise produce a buoyant plume and fallout deposits.

Increasing the thickness and grain size of initial fill amplifies the effects described above, including the time-dependent behavior. For example, a simulation with the same eruptive mixture as described above (adjusted to account for different overburden pressure) but with a 100 m initial fill thickness instead of 50 m produces a jet that initially ascends to ~1.5 km (Fig. 3A). The dense sheath of entrained fill particles results in tendrils that collapse from various heights along the jet margin, much different from a simple fountain. As time progresses, the jet decreases in height to several hundred meters then increases again to ~1.5 km, producing a pulsing behavior with a period of 20–40 s, which contributes to unsteady flow in pyroclastic currents, along with other factors such as small plumes that rise from the currents.

A simulation with the same eruptive mixture as above and with 50 m initial fill thickness (as in Figs. 2B and 2C) but with fill particles having 1 mm diameter instead of 0.1 mm shows that the poorer coupling between gas and larger particles also has an effect on jet dynamics (Fig. 3B). Here the jet drags fill particles upward along its margin as above, but the coarser particles in the dense sheath mix into the core of the jet much more gradually than when they are the same size as the juvenile particles. The juvenile jet core, over-pressured and accelerating to ~300 m/s as it emerges from the fill, maintains a bulk particle density of 3–4 kg/m³ to a height of ~1500 m before the coarser fill particles begin to contribute appreciably to its density. Above ~1500 m, the bulk particle density is ~5 kg/m³ up to a height of ~3500 m, where the density abruptly drops to values that are similar to or less than that of the surrounding ambient air (~0.35 kg/m³). This density drop corresponds to an abrupt transition from negative buoyancy below to positive buoyancy above (Fig. 3B).

At the level of the transition, particles fall back toward the ground along the outer margin of the dense sheath. The buoyancy transition maintains a relatively constant height, fluctuating by only a few hundred meters. Material from the dense sheath collapses along its outer margin during the entire evolution of the jet and overlying buoyant plume, feeding thin pyroclastic currents that are dominated by coarser fill particles. The finer juvenile component mainly falls from the jet top, reaching the ground and increasingly contributing to the currents at later times.

**GEOLOGICAL IMPLICATIONS OF GARGLE DYNAMICS**

The simulated eruptions described above illustrate the complexities that can result from eruption through fresh caldera- or vent-fill deposits, i.e., gargle dynamics. First, the presence of fill can cause an eruption that would otherwise produce a buoyant column and fallout deposits to instead collapse and produce pyroclastic currents and ignimbrites (Fig. 2) with no change in mass flux or volatile content. Unlike in simple fountains that form in the absence of fill deposits, material in these eruptions collapses from all heights along the dense sheath of entrained fill particles. Second, modest increases in fill thickness when the fill and juvenile grain sizes are similar can amplify the complex and transient (pulsing) behavior of the erupting jet even if the eruptive mass flux is constant in time. Third, if the fill material is composed of larger (and/or denser) particles, the resulting jet attains greater heights compared to the same fill thickness with similar juvenile and fill grain sizes due to the poorer...
coupling of larger particles and slower mixing with the fine-grained juvenile jet core. Collapse height and its time variations are expected to influence pyroclastic current behavior and resulting depositional facies.

Detailed field studies of large ignimbrites, although small in number, demonstrate that low-energy, dense and hot pyroclastic currents can be coeval with higher-energy currents that are much more mobile with respect to topography and that are emplaced at lower temperatures (Wilson and Walker, 1985; Fierstein and Hildreth, 1992; Wilson and Hildreth, 1997). Wilson and Hildreth (1997) specifically linked such processes recorded in the Bishop Tuff (California, USA) with eruption from a basin (caldera) containing unconsolidated deposits, coining the term “gargling eruption.” As noted above, material in the dense sheath around a gargling eruption can collapse from a continuous range of heights, and it is to be expected that material from a few kilometers’ height would feed low-temperature, mobile pyroclastic currents, in contrast with material that collapsed from a few hundred meters, depending upon the fill temperature (e.g., Fig. 3B). While our modeling is axisymmetric, in nature it is reasonable to expect spatial variability in availability of fill or vent and/or caldera wall debris, which would lead to asymmetry in development of the dense sheath and pyroclastic currents. There are likely conditions where the dense sheath on one side of a jet feeds pyroclastic currents while the juvenile jet core, still able to mix with air on its unaffected side, becomes buoyant and produces coeval fallout deposits, resulting in so-called intraplinian pyroclastic currents (see also Wilson and Walker, 1985; Neri and Dobran, 1994; Wilson and Hildreth, 1997; Esposti Ongaro et al., 2008). Similar processes were inferred as the origins of complex interstratified fallout and pyroclastic current deposits in proximal products of the 1912 Novarupta eruption (Alaska), which had a very large, debris-filled vent structure as much as ∼2.5 km wide (Hildreth and Fierstein, 2012). Houghton et al. (2004) and Hildreth and Fierstein (2012) interpreted these deposits to have resulted from collapse of over-loaded annular zones caused by recycling of vent fill. Our work provides theoretical backup in favor of such processes; it also strengthens the point made by Houghton et al. (2004) that common density profile assumptions for one-dimensional eruption-column models are incorrect in cases like these.

Material in the dense jet sheath that forms during eruption through fill feeds simulated pyroclastic currents with very low juvenile particle contents. At a horizontal distance of 2000 m from the symmetry axis, the poorly resolved, thin pyroclastic current in the coarse-fill case (Fig. 3B) had no juvenile particles at 150 s and contained only ∼1% juvenile particles at 250 s.

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**Figure 2.** Example of effects of granular caldera fill at 150 s after initiation of a simulated eruption; 900 °C erupting mixture contains 4 wt% H₂O vapor and 0.1-mm-diameter particles. Images represent cylindrical half-spaces, with the left side being the symmetry axis. Colors represent bulk particle density, \( \rho_{bm} = \varepsilon_m \rho_m \) (where \( m \) is particle type, \( \varepsilon_m \) is its volume fraction, and \( \rho_m \) is its material density), on a log scale (see A inset). For comparison, the density of air in the lower part of the domain is \( \sim \)1 kg/m³. (A) With no fill, the eruption has a jet (i.e., gas-thrust) part, driven by initial kinetic energy, which spreads and becomes buoyant above \( \sim \)700 m altitude (model run f2a). (B,C) Same simulated eruption but with a 0.1-m-thick bed of particles representing caldera fill (0.1 mm particle diameter, bed initial particle volume fraction 0.6; run c2a). (B) Bulk density of “juvenile” particles, showing development of pyroclastic currents. Inset shows example of a simple fountain structure that forms when denser erupting mixture is unaffected by fill particles (arrows indicate flow direction; run f1a), for comparison. (C) Bulk density of fill particles, showing how they are dragged up by the erupting mixture and form a dense sheath around it, which then collapses along its outer margins to feed pyroclastic currents with a large proportion of recycled particles (see inset). See Item S2 (see footnote 1).
Figure 3. Effects of fill thickness and grain size, focusing on the area close to the simulated vent. Variables and color scale are the same as in Figure 2; top row of each panel represents juvenile particles and bottom row is fill particles. (A) Same H$_2$O vapor content, mass flux, and particle sizes as in Figures 2B and 2C but with 100 m initial fill thickness (vent conditions modified to account for higher overburden pressure; model run c2b), at three different times. (B) Same H$_2$O vapor content, mass flux, juvenile particle size, and fill thickness as in Figures 2B and 2C but with 1-mm-diameter fill particles instead of 0.1 mm (run c2a2a). Note the different axis scales and times. Horizontal dashed line for 100 s and 240 s shows location of abrupt mixture density decrease. See Item S2 (see footnote 1).
In contrast, at 150 s, the case with 50-m-thick fill but with equal juvenile and fill particle sizes had ~4% juvenile particles at the same distance (Figs. 2B and 2C), and the 100-m-thick fill case had ~2% juvenile particles (Fig. 3A). Thus, thicker and coarser fill material reduces the juvenile component in outgoing pyroclastic currents and their deposits, and in cases where the eruptive jet penetrates very coarse lithic debris, these currents would deposit lithic breccia horizons in the outflow ignimbrite (e.g., Druitt and Bacon, 1986; Yasuda and Suzuki-Kamata, 2018; Valentine et al., 2019). Petrologic and geochemical interpretation of zoned ignimbrites should take these effects into account.

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