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DURATION OF THE BANCO BONITO RHYOLITE ERUPTION, VALLES CALDERA, NEW MEXICO, BASED ON MAGMA TRANSPORT MODELING

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ABSTRACT— Finite volume calculations of the flow of rhyolite are presented to investigate the fate of viscous magmas flowing in planar fractures with length to width ratios of up to 2500:1. Heat and mass transfer for a melt with a temperature-dependent viscosity and phase changes are considered. Magma driving pressures and dike widths are chosen to satisfy simple elastic considerations. These models are applied within a parameter space relevant to the Banco Bonito rhyolite flow, Valles caldera, New Mexico. We estimate a maximum eruption duration for the event of ~200 days, realized at a minimum possible dike width of 5–6 m and driving pressure of 7–8 MPa. Simplifications in the current model may warrant scaling of these results. However, we demonstrate the applicability of our model to magma dynamics issues and suggest that such models may be used to infer information about both the timing of an eruption and the evolution of the associated magma source.

INTRODUCTION

The duration of a volcanic eruption hinges on the preservation of magma pathways from supply to surface, the availability of forces to drive flow, and/or the volume of eruptible magma stored in the source. In degassed silicic systems, high magma viscosities limit flow, leading to the formation of lava domes or thick flows through slow effusion. Sustaining flow of often near-liquidus rhyolite long enough to erupt observed magma volumes requires advective heat transport capable of offsetting conductive heat loss to the surrounding host rock. Whether cessation of an eruption is driven by the freezing of the magma conduit or the exhaustion of the source or magma overpressure holds implications for the magma storage system.

Using a new magma transport model, Truchas (Telluride Team, 2006), we present a study of the sustainability of effusive silicic eruptions. For planar intrusions with realistic, high aspect ratio geometries of 2500:1 to 500:1 (5 km deep by 2–10 m wide), we constrain eruption duration as a function of dike width and driving pressure. Other investigators have addressed comparable problems using similar numerical models. Bruce and Huppert (1990) and Lister and Dellar (1996) constrained the critical widths for basaltic dikes to plug up due to solidification or melt back due to thermal erosion. Carrigan et al. (1992) modeled the effects of converging dike boundaries, viscous dissipation, and rising gas bubbles that may promote flow in narrower conduits. Petcovic and Dufek (2005) evaluated the flow of basaltic magma through a tonalitic crust in order to estimate the duration of the Maxwell Lake dike eruption in the Columbia River flood basalts. Using a similar approach we address transport in dikes as an appropriate tuning exercise for the applicability of our model to the study of magmatic systems.

As a test case we investigate the Banco Bonito (BB) rhyolite lava flow. BB is located on the southwest rim of the Valles caldera, on the edge of the Rio Grande rift in northern New Mexico (Fig. 1). The flow is generally thought to have erupted via a ring fracture dike, similar to earlier postcaldera rhyolite ring domes. With an age of 35–45 ka (Goff and Gardner, 2004), BB represents

the youngest volcanic activity in the Valles caldera. Roughly 0.9 km³ of glassy rhyolite (Self et al., 1991) was extruded from along the caldera ring fracture, producing a flow that extends up to 8 km from the vent (Goff and Gardner, 2004).

The BB flow marked the termination of the El Cajete Series of eruptions (Self et al., 1988), which began with the Battleship Rock ignimbrite and the El Cajete pumice fall (Goff and Gardner, 2004). These magmas consist of low-silica rhyolites containing roughly 73 wt% SiO₂ (Gardner et al., 1986). Following the first two eruption stages, the BB magma was largely degassed, relatively hot at 835–925 °C (Ren, 1997), and carried ~12% phenocrysts by volume (Self et al., 1988).

We begin by introducing our numerical model. Then, we present results of models parameterized for the BB eruption. Finally, we discuss the plausibility of these initial results by comparison to like systems and suggest some implications of the timing of the BB eruption for magma chamber chemistry beneath the Valles caldera.

MODEL SETUP

Numerical approach

We use the model Truchas (Telluride Team, 2006), which solves for conservation of mass, momentum, and energy for multi-material, multi-phase systems,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \mathbf{f}_b \quad (2)$$

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho^L h^L f^L \mathbf{u}) - \nabla \cdot (k \nabla T) = 0 \quad (3)$$

Here \mathbf{u} represents velocity, ρ mixture density, $\boldsymbol{\tau}$ the shear stress tensor, \mathbf{f}_b any body forces (gravity), h the mixture specific volume enthalpy, and h^L and f^L are the liquid specific volume enthalpy and liquid volume fractions, respectively.

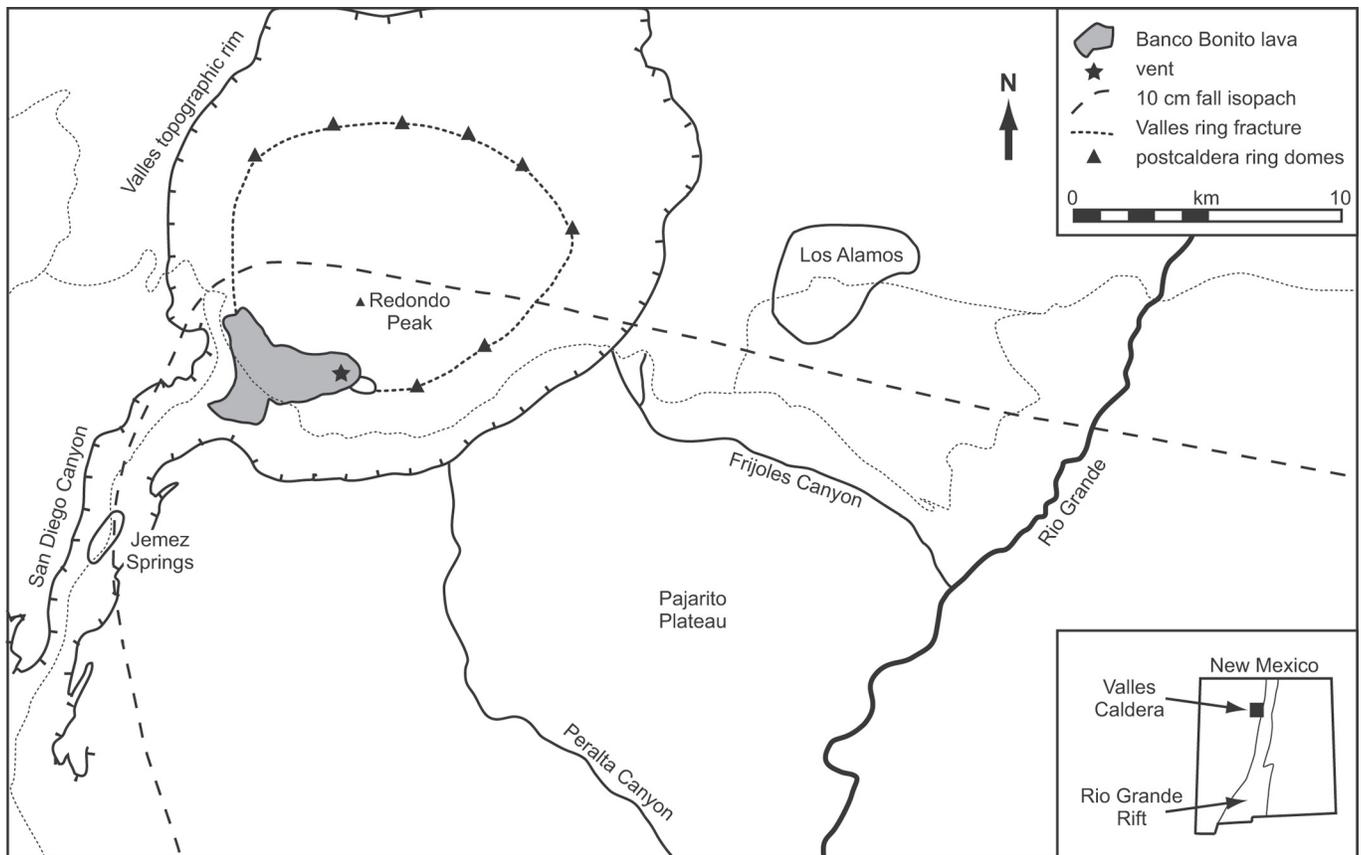


FIGURE 1. Map of the Banco Bonito lava flow (gray) and associated ash fall (dashed line) in the setting of the Valles caldera, New Mexico (after Self et al., 1991).

Truchas allows for the modeling of multiple, consecutive phase transformations for multiple materials of up to two components each. For the preliminary models presented here, we treat rhyolite as a pure material. Phase changes are parameterized to occur non-isothermally, such that a partially solidified mushy zone can develop for temperatures between the liquidus, T_L , and solidus, T_S .

Basic parameters along with modeled values are listed in Table 1, sketched in Fig. 2, and described below.

Dike geometry

Dike dimensions are defined by the magma source depth, a characteristic width, and the length along strike. Fractionation took place at 2.5–7.5 km depth for the Valle Grande rhyolites (Spell and Kyle, 1989). This depth is consistent with the top of a low velocity zone, inferred to contain partial melt, imaged at 5–15 km depth beneath the present Valles caldera via P wave seismic tomography (Steck et al., 1998). Based on these constraints we use a representative depth, or dike height, of 5 km.

Dike width and length are more difficult to constrain in the Valles caldera owing to lack of exposure. Observations of analogous systems along the Jemez lineament and elsewhere in the western United States help in estimating values for these parameters. The minimum dilation for dike intrusion at Inyo Craters, Long Valley, California, is about 10 m (Mastin and Pollard,

1988). Silicic dikes at Summer Coon volcano, Colorado, range in width from 1 to 50 m (Poland et al., 2004), with 10–15 m typify-

TABLE 1. Model parameter values. *The viscosity noted is the value at 900 °C. See Equation (7) for the temperature dependence of viscosity.

Parameter	Value	Source
Magma viscosity*	μ 5×10^5 Pa s	Spera (2000)
Solidus	T_S 750 °C	Eichelberger (1995)
Liquidus	T_L 900 °C	Spera (2000)
Source temperature	T_o 900 °C	Ren (1997)
Host temperature	T_H 200 °C	Steck et al. (1998); Heiken et al. (1990)
Initial dike width	w 2–18 m	
Dike height	d 5 km	Spell (1989)
Dike length	l 5 km	Poland et al. (2004)
Driving pressure	ΔP 2.67–24 MPa	
Melt density	ρ_L 2300 kg/m ³	Bachmann and Bergantz (2004)
Solid density	ρ_S 2600 kg/m ³	Bachmann and Bergantz (2004)
Specific heat	c 1000 J/kg°C	Rubin (1995b)
Magma conductivity	k 1.7 W/m°C	Gable and Shankland (1984)
Latent heat	L 2×10^5 J/kg	Rubin (1995b)
Activation energy	E_a 4×10^5 J/mol	Spera (2000)

ing most exposures (G.A. Valentine, unpubl. 2007). Widths of 10–15 m are also observed in the nearby Mount Taylor Volcanic Field (F. V. Perry, unpubl., 2007). Widths of a few meters to a few tens of meters are therefore plausible.

Our models are two dimensional, and solutions therefore assume infinite extent along strike. However, to compute magma fluxes we must assume some finite length. Rhyolitic dikes at Summer Coon have lengths of a few kilometers, reaching 6.5 km (Poland et al., 2004). The BB lava itself extends for similar lengths along the Valles caldera ring fracture (Fig. 1). Such lengths yield aspect ratios (width to length) of $\sim 10^{-3}$, in line with geologically and geotectically observed geometries (Pollard, 1987). To calculate an eruptive time scale for the ~ 0.9 km³ Banco Bonito rhyolite, we compute erupted volume assuming a dike length of 5 km.

Boundary and initial conditions

Magma flow in our models is driven by a constant excess source pressure. For each possible dike width evaluated in the model, we assume that the driving pressure is comparable to that required to elastically dilate the host rock to that width. Initial width is determined from magma driving pressure via

$$w = \frac{\Delta P}{\mu/(1-\nu)} l \quad (4)$$

with

$$\Delta P = P_M - \sigma \quad (5)$$

where P_M is the internal magma pressure, σ is the remote compressive stress acting perpendicular to the dike plane, w and l are dike width and length, respectively, μ is the elastic shear modulus, and ν is Poisson's ratio (Pollard, 1987; Rubin, 1995a; Rubin, 1995b). Taking $l = 5$ km, $\mu = 5$ GPa (Pollard, 1987; Rubin, 1995a), and $\nu = 0.25$, we obtain $\Delta P = 1.33w$ MPa as a scaling between width and driving pressure.

Based on the Fe-Ti oxide thermometry of Ren (1997), we set the inflow temperature of the magma to the liquidus at 900 °C. The wall rock is initialized at a temperature of 200 °C. This is the base temperature of geothermal reservoirs identified to depths of 2.5 km beneath the caldera (Steck et al., 1998) and agrees with thermal gradients of 60–90 °C/km measured on the southwestern caldera margin (Heiken et al., 1990). Heat is transferred from the hot magma through the cooler wall rock via conduction. Exterior conducting boundaries of the model domain are set as insulating,

$$\frac{dT}{dx} = 0, \quad \frac{dT}{dz} = 0 \quad (6)$$

so no heat escapes from the system during the course of our simulations. Here x is the horizontal direction and z is vertical (Fig. 2).

Viscosity formulation

One of the fundamental properties controlling magma transport is viscosity. In particular, the temperature dependence of sili-

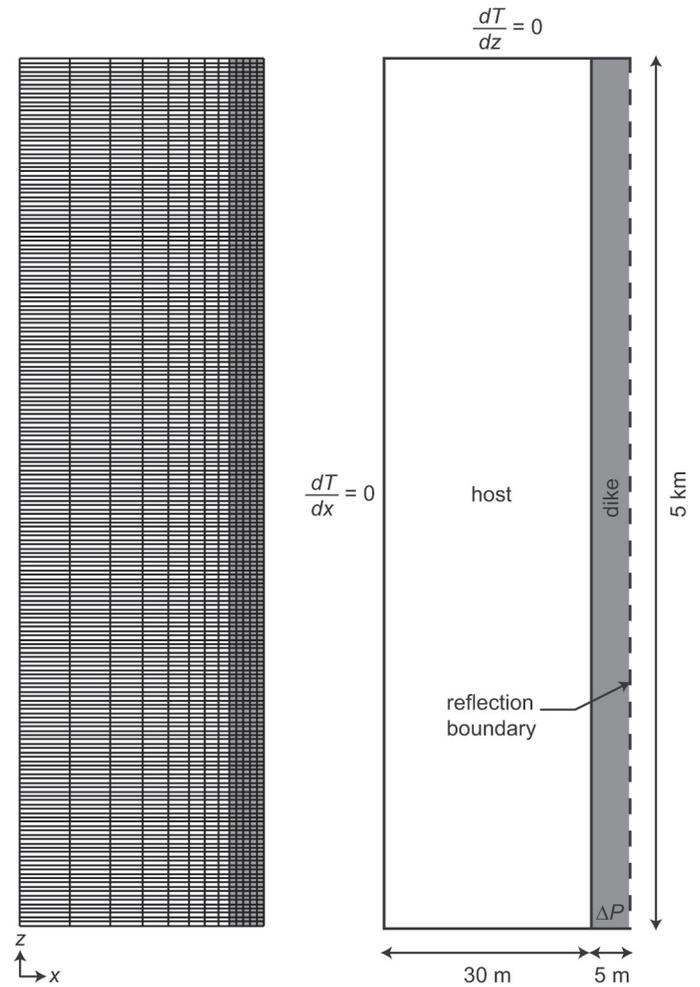


FIGURE 2. Computational mesh for a 10 m-wide dike, together with a schematic showing model dimensions and boundary conditions. The horizontal scale is exaggerated by a factor of 40. Only half of the system was modeled, as there is symmetry about the center of the dike (dashed line).

cate melt viscosity is very strong. We approximate the viscosity of the BB rhyolite by an Arrhenian model,

$$\mu(T) = 7.73 \times 10^{-13} \exp\left(\frac{E_a}{RT}\right) \text{ [Pa s]} \quad (7)$$

where T is the magma temperature, $E_a = 4 \times 10^5$ J/mol is the activation energy for viscous flow, and $R = 8.314$ J/mol°C is the gas constant. This yields a melt viscosity of 5×10^5 Pa s at 900 °C (Spera, 2000).

RESULTS OF NUMERICAL MODELS

We ran models for dike widths between 2 and 18 m, corresponding to driving pressures of 2.67 to 24 MPa (Fig. 3A). The model reveals two types of eruptions, identified schematically in Fig. 3B, which could characterize a system like BB. A maximum eruption duration t_M occurs for a critical dike width w_C through which magma is driven by a critical overpressure ΔP_C . At or

above this level (regime 1), eruption duration represents the time required to extract the 0.9 km^3 volume observed for the BB flow. Below this level (regime 2), eruption is halted by thermal close-off (freezing) of the dike before the required volume is successfully erupted. For BB, the critical minimum width and driving pressure are 5–6 m and $\sim 7\text{--}8 \text{ MPa}$, respectively. The maximum estimated eruption duration approaches 200 days.

DISCUSSION

Model limitations

Several simplifications and assumptions limit the verity and general applicability of our results. First, we presume that magma erupts along a fissure with length equal to the dike length, as opposed to from a localized vent as identified for BB (Fig. 1). The near-surface transition from fissure to vent eruption for systems with planar geometry at depth is well accepted (Bruce and Huppert, 1990; Wylie et al., 1999). We chose to preserve a planar geometry that is likely appropriate to the bulk system that operated below BB. Focusing of magma flow from a dike at depth into a near-cylindrical vent close to the surface could increase eruption times over those presented in Figure 3. The assumed 5 km dike length could also be an overestimate. Reducing the length to 1 km would increase modeled eruption durations by roughly a factor of five. While eruption times may scale with the geometry of the eruptive opening, the critical width and pressure for maintaining a dike at depth should remain reasonably consistent. The width, pressure constraints shown in Figure 3A, as well as the general shape of the proposed curve, should therefore be applicable to BB for the parameters modeled.

Another simplification regarding event duration is our assumption that the BB eruption occurred in a single episode. Goff et al. (1986) presented results from the VC-1 drill core, located west of the BB vent, that clearly identify two separate flow units. A lull in flow, aside from obviously increasing the total time elapsed from the first to last instances of effusion, could further prolong the second phase of the eruption due to increased crystal fractions in the temporarily quiescent conduit.

We prescribe a constant inlet pressure and dike dimensions that vary only due to heat transfer. Dike history models often do presume a stable driving pressure (Rubin, 1995b), which may be appropriate if the source chamber is very large and highly compressible. However, continued modulation of dike geometry during eruption due to variations in driving pressure surely characterizes at least some natural systems (Ida, 1999; Segall et al., 2001). In that sense, many eruptions will descend along the curve suggested by Figure 3, with dike width shrinking as driving pressures wane with time.

Additional model simplifications exist regarding heat and mass transfer within the conduit. We do not include heat generation due to viscous dissipation. Models presented also do not account for retardation of flow through partially solidified porous regions.

Reconciling many of these limitations is of interest for future work. Here we focus on the applicability of a simplified model

that accounts for some of the most fundamental parameters associated with the behavior of effusive silicic dike eruptions.

Comparison to modern analogues

Observations of modern high-silica dome eruptions may help bound expectations for BB. Nakada et al. (1999) summarized the 1990–1995 eruption of Unzen Volcano, Japan, which produced a $\sim 0.1 \text{ km}^3$ dacite dome. This episode at Unzen experienced peak effusion rates of $4 \times 10^5 \text{ m}^3/\text{day}$. A dome erupted at Soufriere Hills between 1995 and 1997, with a volume of $\sim 0.1 \text{ km}^3$ extruded at

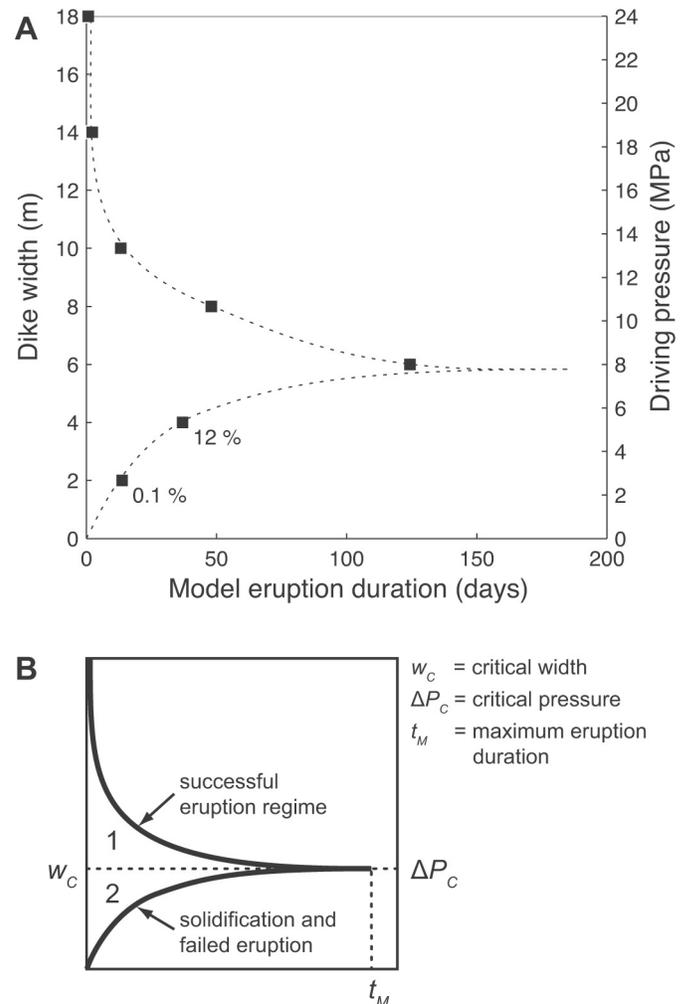


FIGURE 3. Results of numerical models. A. Model time computed for eruption of the Banco Bonito lava as a function of dike width and cognate driving pressure, assuming a 5 km-long dike (black squares). The dotted curve highlights an approximate trend. B. Interpretation of the trend shown in A. The maximum possible eruption duration t_M occurs for a critical width w_c and pressure ΔP_c . Systems operating at or above the critical level (regime 1) can successfully extrude the 0.9 km^3 volume observed for Banco Bonito. Dikes with width, pressure pairs below w_c , ΔP_c (regime 2) would freeze shut before 0.9 km^3 is erupted. The percent of the observed volume erupted for these cases ($w = 2$ and 4 m) is shown in A.

rates of up to 10^6 m³/day (Young et al., 1998). Lavas at these sites were lower in silica, but also cooler than BB, such that melt viscosities may have been similar. Walker (1973) suggests that flow length is the most indicative factor for estimating effusion rate for all compositions including dacites with up to 70% SiO₂. His analysis suggests that a range of effusion rates of $\sim 10^5$ – 10^7 m³/day could produce a flow 5 km long. Even with our assumption of eruption along a 5 km-long fissure, our modeled volume fluxes for 6–8 m-wide dikes fall within the upper limits of this range.

Implications for Banco Bonito source characteristics

The extent to which eruptible magma at depth is depleted may have implications for the composition of the source. That is, possible inferences about the source based on observed lavas depend on what part of the curve in Figure 3 characterizes the eruption in question. In the case of BB, complete extraction of eruptible melt is estimated to occur for dike widths greater than ~ 5 – 6 m. Later stages of such an eruption may tap the transition between largely fluid magma and an underlying, immobile, crystal mush. In this regime, increased concentration of phenocrysts or different phenocryst compositions in the lava might therefore correlate with the end of the eruption. If the eruption ceases due to dike blockage, which is estimated to occur for BB after ~ 200 days for a 5–6 m-wide dike, eruptible magma may remain in the source. In this case, the composition and fraction of observed phenocrysts may not accurately reflect the full state of magma evolution in the chamber.

SUMMARY

We have introduced a new heat and mass transport model for addressing the multiphase dynamics of magmas. While some simplifications are made, the application of our model to the flow of rhyolite in a dike allows us to estimate a range of potential dike geometries and associated eruption durations for the BB obsidian flow. Critical initial dike widths w_c of 5–6 m and driving pressures ΔP_c of 7–8 MPa are estimated as necessary to extract the observed flow volume of 0.9 km³ before dike solidification. These values determine a maximum possible modeled eruption duration t_M approaching 200 days. Below these critical values, the dike would have frozen before the observed volume was extruded. For dikes within a couple of meters width above w_c , effusion rates as assumed for a 5 km-long fissure eruption lie within observed values. Scaling to lower effusion rates and therefore longer eruption times may be more appropriate, given that the BB lava probably erupted from a circular vent that was shorter than the length of the feeder dike at depth. Still, the approach presented here suggests a new way of characterizing eruptions for which the fundamental parameters describing the dike, magma, and extruded volume are known. A more refined model, together with better constraints on the effusion rate of the BB eruption, could permit an estimate of the extent to which the source was exhausted, with implications for the evolution of magma reservoirs beneath the Valles caldera.

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