Reply to the comment by Mike R. James et al. on "It takes three to tango: 2. Bubble dynamics in basaltic volcanoes and ramifications for modeling normal Strombolian activity"

Jenny Suckale,[1] Bradford H. Hager,[1] Linda T. Elkins-Tanton,[1] and Jean-Christophe Nave[2]

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[1] The current paradigm for normal eruptions at Stromboli volcano and Strombolian-type activity more generally posits that each eruption represents the burst of a large pocket of gas, commonly referred to as slug, at the free surface of the magma column. This slug model has been investigated and refined primarily through analog fluid dynamical experiments at the laboratory scale. There is no doubt that these studies have advanced our understanding of Strombolian eruptions considerably. However, given the very fundamental status of the slug model for our current thinking about Strombolian-type eruptions, it is paramount to carefully assess all underlying assumptions of the model. One important uncertainty lies in the scaling behavior of the observed slug dynamics in the laboratory. Scale invariance requires all nondimensional numbers to be identical, but it is generally not feasible to match all of the nondimensional numbers characterizing the volcanic conduit exactly in a laboratory experiment. Numerical computations offer a means of directly comparing slug dynamics at drastically different scales [*Suckale et al.*, 2010b]. We find that the very large slugs in volcanic conduits are more prone to dynamic instabilities and breakup than the comparatively small slugs in laboratory settings. This finding in itself does of course not 'disprove' the slug model: it merely points to potentially important differences in slug stability at volcanic scales as opposed to laboratory scales.

[2] Being careful and critical of the errors and interpretations of numerical simulations is important; similarly, the appropriateness of laboratory analogs must also be examined. *James et al.* [2011] raise a valid point asking whether our simulations are capable of reproducing stable slug rise in water. Figure 1 shows a computation performed for the experimental parameters provided by *James et al.* [2011]. In agreement with the analog experiments, we do indeed find that this slug rises stably in water, i.e., the slug ascends buoyantly within the conduit without experiencing 'catastrophic' breakup as defined by *Suckale et al.* [2010b]. Thus the experiments by *James et al.* [2011] do not appear to contradict our computations. We also reproduce computationally stable slug flow at finite Reynolds number (Re) shown in the experiment specified by *Jaupart and Vergniolle* [1989] [*Suckale et al.*, 2010b]. It is worth noting that in both cases, the set of nondimensional numbers characterizing the experiment are not identical to those thought to be representative of the volcanic conduit and thus potential differences in the fluid dynamical behavior are not unexpected.

[3] That we observe stable slugs in water but not in magma supports an argument raised by *James et al.* [2011], namely that Re is an insufficient parameter for comparing slug dynamics at different spatial scales. We welcome their discussion of the drawbacks of using a single Re to describe slugs. Focusing on Re to characterize our computations was a purely pragmatic decision: First, Re is commonly used for the purpose of comparing fluid dynamical computations at different scales. Second, we were able to use estimates for Re characterizing Strombolian slugs based on observational data measured at Stromboli [*Vergniolle and Brandeis*, 1996]. Third, we observed a correlation between Re and breakup within the regime we investigated, which is not unexpected since Re is an indirect measure of the size of a gas bubble or slug. That being said, a more comprehensive set of nondimensional numbers is undoubtedly needed to evaluate scaling behavior of slugs for different fluid dynamical regimes, including nondimensional criteria that capture the wavelength of potential interface instabilities in relation to the curvature of the interface and the time scale associated with instability growth to the time scale associated with advection of the instability along the interface. Our study is a first step toward gaining a better understanding of slug stability.

[4] From a theoretical point of view, very large and dynamic gas volumes are not expected to be indefinitely stable. The light gas slug moves underneath a column of very heavy magma and this unstable density stratification is prone to the formation of Rayleigh-Taylor instabilities at the essentially flat upper surface of the slug. *Grace et al.* [1978] developed a semiempirical rationalization of this process that affords rough estimates of maximum stable sizes as listed in Table 1 of *Suckale et al.* [2010b]. The appeal of this model lies primarily in its simplicity, but this very simplicity also

[1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.
[2]Department of Mathematics and Statistics, McGill University, Montreal, Quebec, Canada.

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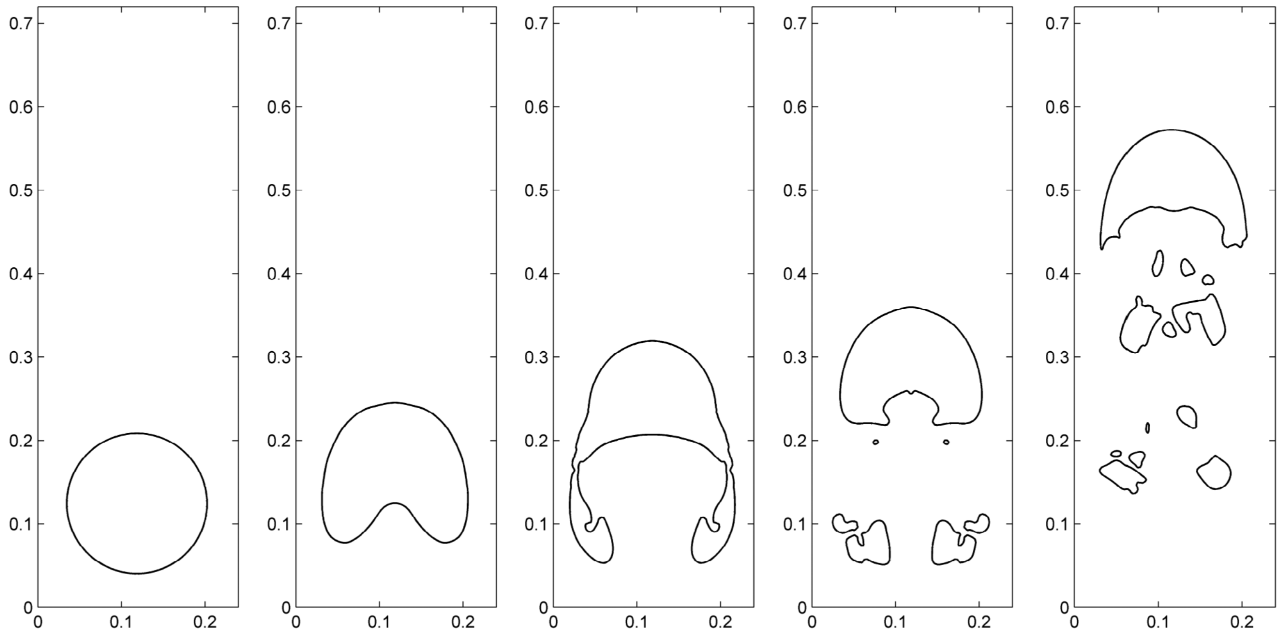

Figure 1. Slug rise in water based on the experimental parameters specified by *James et al.* [2011]. The computation was performed in two dimensions with a grid of 80 × 240 cells.

limits the predictive value of the obtained bubble sizes to order-of-magnitude estimates as discussed in more detail by *Batchelor* [1987]. The discrepancy factor of ≈1.65 between the sizes obtained by *James et al.* [2011] and those cited in Table 1 of *Suckale et al.* [2010b] is very likely exceeded greatly by the errors associated with the model estimates and is therefore of limited practical relevance. The slight discrepancy itself is easily resolved, because our estimates of the maximum stable sizes rely on a numerical computation of bubble rise speeds while *James et al.* [2011] use the empirical estimation procedure outlined by *Grace et al.* [1978] to compute bubble rise speeds. Overall it is not surprising that the Grace rationale does not capture all the details of the breakup sequences we observe, but given the lack of a more comprehensive theory of breakup it is encouraging that expected and observed bubble sizes roughly coincide.

[5] *James et al.* [2011] also raise the question whether our numerical approach can accurately resolve slug dynamics. Multiphase flow with rapidly deforming interfaces is challenging to resolve accurately and a debate about numerical results is thus inevitably linked to a debate about the numerical methodology. Because of the complexity of accurately capturing the force balance along dynamic and deforming interfaces, it is common to neglect certain aspects of the problem in numerical implementations. Previous numerical treatments of slugs in magmatic systems are no exception. For example, *James et al.* [2008] present simulations of slugs in which the slugs are assumed to be void, thus neglecting the flow field inside the slug and the jump conditions at the interface. Another common approach is to make use of diffuse interface theory to simplify the problem [*D'Auria and Martini*, 2009], which entails artificial smearing of the interface between magma and gas. The artificial smoothing removes the discontinuities associated with the interface, thereby obviating the need to compute jump conditions. Finally, Lattice-Boltzmann simulations have been used [*O'Brien and Bean*, 2008], which supersede solving the Navier-Stokes equation entirely, replacing it with a series of collision and stream steps.

[6] In contrast, our numerical methodology was developed specifically for the purpose of being able to resolve interface instabilities in two-phase flow characterized by rapidly deforming interfaces and large viscosity contrasts. We fully resolve the fluid dynamics in both fluids, carefully evaluate the various jump conditions at the interface, and track the interface accurately as a sharp boundary over time. We also validate and benchmark our code in detail in a separate paper [*Suckale et al.*, 2010a]. Since the main novelty of our code is a rigorous treatment of the jump conditions at Re = 0, we focus on that regime. At finite Re, the methodology we use to resolve the detailed interface dynamics is well established and has been validated extensively in previous studies [*Liu et al.*, 2000; *Kang et al.*, 2000; *Nave et al.*, 2010].

[7] Apart from the numerical methodology, *James et al.* [2011] also express doubts regarding the initial condition we use in our simulations. We chose to initiate our simulations with spherical gas volumes for two reasons. First, while we have investigated several initial conditions, a spherical shape introduces the greatest initial stability: Other interface shapes may be prone to instability where spherical forms are not [e.g., *Pozrikidis*, 1990]. Second, the estimated volume of Strombolian slugs, approximately 20–35 m^3 [*Ripepe and Marchetti*, 2002], implies that the equivalent radius is comparable to the conduit radius. Therefore, Strombolian slugs are presumed to have an aspect ratio (i.e., length/width) of approximately 1 as approximately captured in a spherical initial condition. That being said, it is certainly possible that we would observe different breakup sequences for more elongated slug geometries which we did not investigate. *James et al.* [2011] suggest extending the run time of the

simulations but accumulation of numerical error becomes a concern for very long run times, in particular after significant breakup sequences occurred.

[8] Concluding, we would like to thank *James et al.* [2011] for their contribution and for the opportunity to clarify and enrich our arguments. Undoubtedly, analog experiments and numerical computations are best used in conjunction as they have different advantages and drawbacks. Computations allow bridging the drastically different scales between laboratory and volcano and indicate that differences in the set of nondimensional numbers characterizing the two different systems may translate into differences in slug stability. For example, our simulations indicate that Strombolian-type slugs in magmatic systems become unstable at low to intermediate Re [*Suckale et al.*, 2010b]. Slugs in water, on the other hand, might not, as evidenced both by computations (see Figure 1) and experimental results [*James et al.*, 2011]. Similarly, more elongated slugs might have different stability properties. There is no doubt that more work is needed to comprehensively evaluate the fluid dynamical conditions for slug stability in magmatic systems. One key priority is to identify the relevant physical parameters that determine the formation of interface instabilities for various initial conditions, slug shapes, slug sizes, and fluid properties as well as the corresponding nondimensional numbers. In volcanic systems there are also other factors that might contribute to slug instability such as the presence of an ambient flow field in the conduit, the presence of crystals in the fluid and similar complexities. Computations can contribute to the goal of developing a better understanding of slug instabilities, but accurate simulations of interface dynamics remain challenging and codes that do not attempt to resolve the interface are not well suited for investigating the onset of interface instabilities.

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L. T. Elkins-Tanton, B. H. Hager, and J. Suckale, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. (suckale@mit.edu)

J.-C. Nave, Department of Mathematics and Statistics, McGill University, Montreal, QC H3A 2T5, Canada.