Comment on "It takes three to tango: 2. Bubble dynamics in basaltic volcanoes and ramifications for modeling normal Strombolian activity" by J. Suckale, B. H. Hager, L. T. Elkins-Tanton, and J.-C. Nave

Mike R. James,[1] Edward W. Llewellin,[2] and Stephen J. Lane[1]

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1. Introduction

[1] Strombolian eruptions are usually attributed to the ascent of conduit-filling "slugs" of magmatic gas through a more-or-less stagnant magma column, and the subsequent bursting of those slugs at the surface. A sufficiently large body of literature exists that adheres to this view that it may be considered paradigmatic [e.g., *Aster et al.*, 2003; *Blackburn et al.*, 1976; *Chouet et al.*, 1974, 2003; *Gerst et al.*, 2008; *James et al.*, 2009; *Jaupart and Vergniolle*, 1989; *Parfitt*, 2004; *Ripepe et al.*, 1996, 2007; *Rowe et al.*, 2000; *Vergniolle and Brandeis*, 1996; *Vergniolle et al.*, 1996]. *Suckale et al.* [2010a] present a numerical investigation of the dynamics of gas bubbles during buoyancy-driven ascent through a stagnant liquid and conclude that slugs are unstable for Reynolds numbers, $Re \approx O(10)$ or larger (where they define $Re = \rho_f v_0 a/\mu_f$, with ρ_f and μ_f the liquid density and viscosity respectively, a the slug radius and v_0 the slug rise speed, and $O(10)$ represents "of order 10"). Applying their analysis to Stromboli volcano, Italy, they conclude that slugs cannot stably ascend the conduit unless it is filled with magma that has an improbably high viscosity (greater than $O(10^4)$ Pa s). The implication is that eruptions at Stromboli are not caused by gas slugs, and that a new paradigm is required.

[2] In this comment, we argue that the simulations employed by *Suckale et al.* [2010a] are not well posed to assess the stability of slugs. *Suckale et al.* [2010a] present only simulations of short duration (ascents of ~2 bubble radii in their Figure 11). In these, "real" instabilities cannot be distinguished from motions associated with flow development arising from the initial conditions of a stationary fluid and a circular bubble geometry, which cannot be representative of nature. Consequently, although we do not query the quality of the fluid dynamic model itself, we argue that the interpretations of the simulations presented in terms of overall slug stability are inappropriate, and result in poorly supported conclusions. Given the potential significance of the claims regarding slug stability made by *Suckale et al.* [2010a], we believe that they bear a strong burden of proof; however, they present no quantitative validation of their slug rise modeling (such as comparison with some of the large volume of experimental data on laboratory-scale slugs collected over the last fifty years: see extensive compilations in the work of *White and Beardmore* [1962] and *Viana et al.* [2003]) and no comparison is made with other computer simulations of stable slug flow for engineering [e.g., *Feng*, 2008; *Taha and Cui*, 2006, and references therein] or volcanological [e.g., *D'Auria et al.*, 2004; *D'Auria and Martini*, 2009; *James et al.*, 2008; *O'Brien and Bean*, 2008] scenarios.

[3] For brevity, we restrict our comment to two areas: first we highlight issues in the application of the model to gas slugs; second, we demonstrate that the use of Reynolds number by *Suckale et al.* [2010a] to describe the field of slug stability is inappropriate. Throughout our comment we assume that the equation of *Suckale et al.* [2010a] for viscosity ratio, Π_1, (their equation 12) is incorrect as printed, and that it should read $\Pi_1 = \mu_g/\mu_f$, where μ_g is the gas viscosity. In this way, the Π_1 values of 10^{-6} given within the paper reflect a gas phase that is less viscous than the liquid phase. Furthermore, we are not able to reproduce the values given by *Suckale et al.* [2010a, Table 1] for the maximum stable bubble radii of bubbles in infinite media, calculated using the theoretical approach of *Grace et al.* [1978]. We calculate values that are larger than the quoted values by a factor of ~1.65 (Table 1, and see auxiliary material for a detailed explanation of its derivation).[1] Furthermore, if a value for magma density of 2600 kg m^{-3} is assumed, which we suggest is more appropriate for most basaltic magmas [e.g., *Murase and McBirney*, 1973] than the value of 3500 kg m^{-3} assumed by *Suckale et al.* [2010a], then we calculate values of the maximum stable bubble radius that are approximately double the values presented by *Suckale*

[1] Lancaster Environment Centre, Lancaster University, Lancaster, UK.
[2] Department of Earth Sciences, Durham University, Durham, UK.

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010JB008167.

Table 1. Amended Version of *Suckale et al.* [2010a, Table 1] for Maximum Stable Bubble Radii in a Liquid of Infinite Extent[a]

Magma Viscosity (Pa s)	Maximum Bubble Radius (m)	
	Liquid Density of 3500 kg m^{-3}	Liquid Density of 2600 kg m^{-3}
10	0.11	0.13
25	0.19	0.23
50	0.30	0.37
75	0.39	0.48
100	0.48	0.58
250	0.88	1.07
500	1.39	1.70
750	1.82	2.22
1000	2.20	2.70

[a]We are unable to reproduce the values given by *Suckale et al.* [2010a] for a liquid density of 3500 kg m^{-3}; our calculated values are greater by a factor of ~1.65. We additionally provide values for a liquid density of 2600 kg m^{-3}, a density that we suggest is more representative of basaltic magmas [e.g., *Murase and McBirney*, 1973]. See auxiliary material for derivation of the table values.

et al. [2010a, Table 1]. Note that our observations regarding these calculations for bubbles in infinite media are secondary to our main concerns, which center on the interpretation of the slug simulations.

2. Gas Slug Stability in Basaltic Systems

[4] The numerical approach used by *Suckale et al.* [2010a] is derived from the Stokes flow model of *Suckale et al.* [2010b] and combines the level set method with an extended ghost fluid and the extension velocity technique, in order to solve the equations for buoyancy-driven Navier-Stokes flow in the presence of large viscosity contrasts. The model is developed to represent discrete and deformable fluid interfaces where surface tension is important, such as in the interactions of small gas bubbles in basaltic magmas. In the work of *Suckale et al.* [2010a] the model is used with parameters appropriate for Stromboli volcano to investigate bubble stability, coalescence and breakup, including analysis of the behavior of conduit-filling gas slugs. Although *Suckale et al.* [2010b] use four scenarios to validate their Stokes model, validation of the Navier-Stokes variant, which is used throughout *Suckale et al.* [2010a], appears limited to the presentation of steady state shapes of three simulated slug bubbles (their Figure 12), and the statement in their Figure 3 caption; "a comparison with the shape regimes for bubbles during buoyant ascent [*Grace et al.*, 1976] confirms that we reproduce the expected steady state shape correctly in our computations." No quantitative comparison with published experiments or numerical simulation is presented to help provide confidence in their Navier-Stokes model.

[5] In their analysis of slug stability, *Suckale et al.* [2010a] summarize the results of 69 two-dimensional simulations (their Figure 10). The conditions for the simulations are located within a space defined by the Reynolds number and the Bond number, $Bo = \Delta\rho g a^2/\sigma$, where $\Delta\rho$ is the density difference between the fluids, g is the acceleration due to gravity and σ is the surface tension. Two regimes are identified: at $Re > 8$ slugs are observed to breakup; at $Re < 8$ slugs are stable, and, for the simulations presented, stability did not depend upon Bond number. The nature of the slug breakup is demonstrated in their Figure 11, which presents results of three simulations of gas slugs in basaltic systems with $Re \approx 10$, 50 and 80. Their models show small bubbles leaving the base of the slugs, with their size and frequency increasing with Re (paragraph 46). At $Re \approx 80$ the example shown is one of "catastrophic breakup," where the slug is disrupted into four bubbles.

[6] On the basis of these simulations, *Suckale et al.* [2010a] conclude (paragraph 56) that "…slugs are prone to dynamic instabilities if they are characterized by $Re \approx O(10)$ or larger" and that "…a slug at $Re \approx 80$ would break up catastrophically within seconds after formation." This is not consistent with experimental observations. In laboratory experiments (i.e., with slugs of diameter O(cm or dm)), a limiting Reynolds number for slug stability has not been identified and slugs are routinely observed with $Re > 10^2$ [e.g., *Campos and Guedes de Carvalho*, 1988; *van Hout et al.*, 2002; *Viana et al.*, 2003; *White and Beardmore*, 1962; *Zukoski*, 1966]. *Suckale et al.* [2010a] suggest that the discrepancy between laboratory data and their simulations is due to experiments "scaling differently" from the simulations (paragraph 59) because the laboratory scales are within the stable size range calculated for bubble diameters in infinite media (Table 1) whereas basaltic systems may not be. Unfortunately, they do not reinforce their argument by demonstrating that the appropriate length scale–dependent physics is represented in their code by simulating stable $Re \approx O(10–100)$ slugs at the laboratory scales for which a wealth of experimental data exist.

[7] It is worth noting at this stage that the bulk of engineering research on slug flow concerns concurrent and continuous flows of low viscosity liquid-gas systems [e.g., *Cheng et al.*, 2008, and references therein] and care has to be taken in translating such results to individual gas slugs in stagnant (or low velocity) basalt melt. Phrases in engineering literature such as "in pipes with very large diameters, slug bubbles cannot exist" [*Schlegel et al.*, 2009] are invariably subject to caveats often taken for granted within the engineering field, and refer only to continuous concurrent flows of low viscosity fluids. Under such conditions, liquid motion ahead of the slug (either from the liquid flow or from the wakes of preceding slugs) can affect slug stability [e.g., *Mishima and Ishii*, 1984] and stability fields cannot be extended to single slugs in stagnant media of greater viscosities.

[8] The theory behind the bubble size stability limit relies on the growth of Rayleigh-Taylor instabilities at the top of the bubble, so the implication is that, at the volcanic scale, slugs would be affected by Rayleigh-Taylor instabilities. However, as *Suckale et al.* [2010a] describe (paragraph 47 and Figure 11), their simulations show the bulk of the pre-breakup bubble deformation occurs at the base of the slug rather than at the top (the same process is also shown in their Figure 4). Consequently, the model results are not consistent with catastrophic breakup that is dominantly due to either Rayleigh-Taylor instabilities [*Clift and Grace*, 1972; *Grace et al.*, 1978] or the Kelvin-Helmhotz instabilities mentioned in their paragraph 51; however an alternative mechanism to explain the proposed "dynamic instability" is not elaborated.

[9] Here we suggest that the slug deformations shown in Figure 11 (and the catastrophic bubble breakup in Figure 4) result from the initial development of the liquid velocity

field from the unstable stationary starting conditions imposed in the model. In many ways, the model results appear similar to the description by *Clift and Grace* [1972] of bubble splitting in lead shot beds fluidized by water, where splitting developed from the base of bubbles immediately following bubble injection. This splitting was attributed to an entrance effect in which initialization of the developing bubble wake resulted in sufficient upward momentum for the wake to reach the roof of the bubble (an explanation that appears consistent with the bulk of the slug deformation shown in Figure 11c of *Suckale et al.* [2010a]).

[10] For their two dimensional simulations, *Suckale et al.* [2010a] use initial fluid conditions of a stationary circular bubble in liquid bounded by vertical no-slip walls, representing a perpendicular cross section through a long, horizontal cylindrical bubble in a dike-like magma body. By using the equivalent of a circular gas pocket in the initial conditions, this type of model is straightforward to interpret when addressing scenarios in which surface tension effects are significant (e.g., for small bubbles). However, for larger buoyant bubbles and slugs in basaltic systems where shapes and velocities are determined by inertial dynamics, gravitational and viscous effects [*Seyfried and Freundt*, 2000], the influence of surface tension is negligible and a stable "static" initial shape does not exist. Consequently, even if a realistic "dynamic" bubble shape were incorporated as an initial condition, the bubble could not be assumed maximally stable unless an appropriate liquid velocity field were also defined. Under such unstable initial conditions (as shown in Figures 4c, 5, and 11c), in order to conclusively distinguish instabilities that may arise under "real" flow conditions from those resulting from start-up effects, simulations must be run for sufficient time for flow to become fully developed. In the laboratory experiments of *James et al.* [2006], gas slugs disrupted in a section of tube that flared to 8 cm diameter, coalesced back into a stable slug within ~6 slug radii (for $Re \approx 140$). The conclusions regarding slug instability that are drawn by *Suckale et al.* [2010a] are based on simulations of ascent through only ~2 slug radii.

[11] We note that *Suckale et al.* [2010a] do not compare their results with other numerical models of slugs, which have been run at a range of scales over the last twenty years or so (recent examples include *Taha and Cui* [2006], *Feng* [2008], and *Kang et al.* [2010]). In terms of slug stability, their conclusions are at odds with the results of models that have successfully reproduced slug flow within basaltic volcanic systems (none of which are discussed or cited within *Suckale et al.* [2010a]) [e.g., *D'Auria et al.*, 2004; *D'Auria and Martini*, 2009; *James et al.*, 2008; *O'Brien and Bean*, 2008] using a variety of different techniques. Most recently, using commercial code, *Chouet et al.* [2010] successfully simulated slug flow at $Re > 330$ in order to interpret seismic data from Kilauea. Interestingly, at $Re \approx 2000$, the diffuse interface models of *D'Auria and Martini* [2009], in which bubbles and slugs were simulated ascending distances of ~20 conduit radii to the magma surface, showed daughter bubbles very similar to those of *Suckale et al.* [2010a], generated shortly after the start of the simulations, and during ascent. However, these bubbles and slugs did not break up catastrophically and, in terms of gas volume, depressurization expansion of the gas more than accounted for gas mass lost into daughter bubbles and Strombolian-like slugs were simulated to reach the magma surface. It is also important to recognize that multiple trailing daughter bubbles are usual for slugs with turbulent wakes [e.g., *Santos et al.*, 2008, Figure 6]. Such trailing bubbles do not necessarily signify steady breakup of the slug, and can ascend with the slug, fully entrained within the wake vortices [*Viana et al.*, 2003]. In the case of Stromboli, a further factor to consider is conduit inclination [*Chouet et al.*, 2003, 2008]. For inclined conduits, slug flow is naturally promoted because the gas volume fraction within the magma is enhanced at the upper conduit boundary [*James et al.*, 2004]; furthermore, such slugs have asymmetric morphologies [e.g., *Zukoski*, 1966] and stability limits for vertical conduits will not necessarily apply.

3. Gas Slugs and Reynolds Number

[12] Finally, we would like to consider whether the slug Reynolds number, as used by *Suckale et al.* [2010a], is an appropriate parameter to describe gas slug stability. As a ratio representing the relative importance of inertial over viscous forces, Reynolds number is used effectively to describe laminar to turbulent transitions in fluid flows and in bodies moving through fluids, but complexities arise in its interpretation with the ascent of gas slugs. The sometimes-quoted slug Reynolds number emerges from the use of Reynolds number with bubbles and drops in infinite media, where the length scale used is bubble radius or diameter, and *Re* provides a measure of the wake turbulence. For gas slugs, the radius or diameter is determined by the tube wall and the dynamics of the falling liquid film and, for long slugs, velocity (hence also *Re*) is independent of gas volume. Slug velocity is controlled by the rate at which liquid can drain into the falling film behind the nose, the dynamics of which will be controlled by the film thickness rather than the slug diameter, so film thickness would be the required length scale for a Reynolds number appropriate for this region. At the base of the slug, where the falling film impinges on the liquid under the slug, a further formulation of Reynolds may assist with determining whether the slug wake is laminar, develops a vortex, or is turbulent and entrains small bubbles [*Campos and Guedes de Carvalho*, 1988; *Nogueira et al.*, 2006]. So, depending on which region of the slug is of interest, different Reynolds numbers will be appropriate. We suggest that slug Reynolds number is not suitable for analyzing slug stability, and particularly should be avoided if it does not capture the proposed relationship between stability and slug diameter. We note also that, strictly, Reynolds number is only applicable to steady conditions where flow has time to develop fully, so should only be used to describe developing flows, in finite media, under carefully described caveats.

4. Summary

[13] *Suckale et al.* [2010a] use a computational fluid dynamics model to propose a stability limit for gas slugs in low viscosity magmatic systems, based on slug Reynolds number. Their conclusions are not in line with the geophysical data, field observations and previous modeling work that have guided current thinking. We suggest that

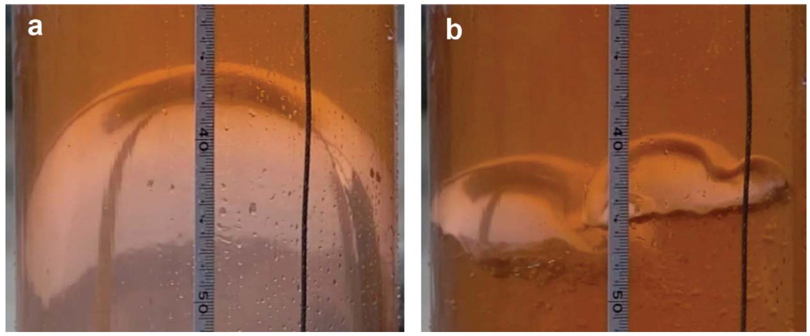

Figure 1. Still images taken from high-speed video imagery of a slug (Figure 1a) and two bubbles (Figure 1b) of air, rising through dyed water in a 12 m long, vertical cylindrical pipe (internal diameter ~0.24 m). Camera was ~5 m below the pipe top and scales shown are in centimeters. Approximate material properties, at experimental temperature of 10°C, are liquid density, 1000 kg m^{-3}, gas density, 1.226 kg m^{-3}, liquid viscosity, 1.5 mPa s and surface tension 0.075 N m^{-1}; in both cases, the liquid column was stagnant when the gas entered the pipe. The experimental results contradict the conclusions drawn by *Suckale et al.* [2010a] that slug stability requires either that $Re < O(10)$ or that slug radius is smaller than the maximum stable bubble radius in an infinite medium for the same material properties. (a) A stable slug nose, after an ascent of ~13 s. From the video imagery, the slug radius, $a \approx 0.12$ m, the slug rise velocity, $v_0 \approx 0.54$ m s^{-1} and the slug length is ~0.24 m. Calculated values for dimensionless parameters as defined by *Suckale et al.* [2010a] (their equations 9, 10, 11 and 13; note the unusual use of radius rather than diameter in the Froude number, Fr) are $Re \approx 40{,}000$; $Fr \approx 0.27$; $We \approx 430$; $Bo \approx 1600$. (b) Unstable gas bubbles. A large instability can be seen in the top of the rightmost bubble; in the video imagery, this instability can be seen to develop, grow and detach a small bubble (which then subsequently coalesces back with its parent). The stable slug nose shown in Figure 1a is much wider than the unstable bubbles; the rightmost bubble has an approximate width of 0.13 m, and a rise velocity of $v_0 \approx 0.59$ m s^{-1} is calculated from video imagery. The videos are available in the auxiliary material.

they reflect the difficulties of initializing numerical models rather than indicating a fundamental stability limit. A more robust investigation of slug instability would illustrate a stable slug being driven into instability, perhaps as it ascends a gently widening conduit, and would use a model that is demonstrated to be capable of reproducing key parameters of laboratory slug flows, such as ascent velocities (e.g., see the compilations of *Viana et al.* [2003] and *White and Beardmore* [1962]). Such an approach would provide confidence in a parameterization of slug stability and could raise interesting questions for the existing numerical codes that can simulate large stable slugs in low viscosity basaltic systems, but were not discussed by *Suckale et al.* [2010a]. Figure 1 presents experimental evidence that contradicts the conclusions drawn by *Suckale et al.* [2010a] regarding slug stability (namely that stability requires either that $Re < O(10)$ or that slug radius is smaller than the maximum stable bubble radius in an infinite medium for the same material properties). In water, the maximum stable size for a rising air bubble is given by a spherical volume equivalent radius of ~0.025 m [*Clift et al.*, 1978]. Nevertheless, in Figure 1a, a fully developed stable slug with a nose free from instability, rises up a water-filled cylindrical pipe of internal diameter 0.24 m ($Re \approx 40{,}000$). In Figure 1b, a bubble with a width of ~0.13 m in the same pipe demonstrates a well developed Rayleigh-Taylor instability, similar to the images of a splitting bubble in a sugar solution given by *Clift and Grace* [1972]. Clearly, the bubbles here are outside the stable size range for isolated bubbles, yet larger, stable slugs with $Re \gg O(10)$ can be formed. Videos of the ascent of the slug and bubbles are available in the auxiliary material.

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M. R. James and S. J. Lane, Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK. (m.james@lancaster.ac.uk)

E. W. Llewellin, Department of Earth Sciences, Durham University, Science Labs, Durham DH1 3LE, UK.