New Insight Into a Volcanic System: Analogue Investigation of Bubble-Driven Deformation in an Elastic Conduit

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Abstract

Analogue and numerical simulations have been widely used to describe the mechanisms of bubble and slug ascent during volcanic eruptions as well as their formation and explosion mechanisms. Nevertheless, little is known about the mechanical interaction between the fluid and the surrounding medium. In this work, we report the results from analogue experiments designed to show how deformation of the conduit walls induced by the rising slugs is related to the radiation and propagation of seismic and geodetic signals. For the first time, we investigate the dynamics of bubbles in an elastic conduit unveiling the relationship between slugs and crustal strain accumulation around the conduit. Moreover, we discuss the retroactive effects of the deformed conduit wall on the dynamics of a rising slug, particularly, how the flow is affected, and the eventual implications on the intensity of the eruption. Our results show that the combination of an elastic conduit with a large volume of gas may lead to the development of a new type of slug, here defined as a “super slug,” characterized by tapering towards the tail and a much higher ascent velocity and inner pressure compared with ordinary slugs. This newly observed behavior could be linked to vigorous explosive events.

1. Introduction

The dynamics of gas slugs, which are large gas bubbles that fill almost the entire cross section of a conduit, has been widely studied in several fields, from engineering, where slug flow has numerous industrial applications, encompassing hydrocarbon production and transportation (Morgado et al., 2016), to physiology (Martynov et al., 2009), where the formation and mobilization of microbubbles in blood vessels can be harmful. In geological systems, large gas slugs rising through the stagnant magma are often observed during Strombolian activity (Genco & Ripepe, 2010; Pering et al., 2015; Pino et al., 2011; Seyfried & Freundt, 2000). Fluid mass transport is believed to have a major role in generating seismicity at persistently active volcanoes, with the gas slug ascent in relatively low-viscosity magmas considered as one of the possible driving mechanisms of volcanic eruptions (Chouet et al., 2003; Lane et al., 2004; O’Brien & Bean, 2008; Ripepe et al., 2001). The link between the behavior of gas slugs rising the volcanic conduit and the eruptive style they cause has been analyzed in several studies (Del Bello et al., 2012; Gaudin et al., 2017; James et al., 2008; James et al., 2009; Seyfried & Freundt, 2000), with other investigating the geophysical signals generated (Chouet et al., 2003; James et al., 2006; Vergniolle & Brandeis, 1996). Linking the signals recorded at the surface with slugs rising in the conduit can help us estimate parameters related to the volcanic system such as volume and mass of gas involved and thus more accurately forecast future events.

Geodetic signals such as tilt have been reported at many volcanoes in relation to slug ascent preceding gas bursting (i.e., the explosive event) during Strombolian and small Vulcanian eruptions (Genco & Ripepe, 2010; Iguchi et al., 2008; Kamo & Ishihara, 1989; Lyons et al., 2012; Nishi et al., 2007; Nishimura et al., 2012; Wiens et al., 2005). At Stromboli Volcano, explosions are accompanied by ground deformation (<100 nrad) linked to small inflation-deflation cycles (~250 s long) related to gas discharge/recharge cycles happening in the volcanic conduit (Genco & Ripepe, 2010). Tilt data recorded during gas bursts observed at Semeru Volcano, Indonesia, exhibit a short duration (~30 s) and a small displacement (~tens of nrad), proportional to the associated seismic energy (Nishimura et al., 2012). Conversely, very long period seismic signals (VLP) linked to the slug ascent and the forces generated during its interaction with the surrounding medium have also been extensively reported. At Hachijo Island, Japan, VLPs have been observed with a...
period of 10 s (Kumagai et al., 2003), while at Mount Erebus, Antarctica (Aster et al., 2003), VLPs displayed periods between 8 and 20 s. At Stromboli, VLPs had periods ranging from 2.5 to 14 s (Chouet et al., 2003). These observations are believed to represent ascending slugs and therefore imminent volcanic eruptions.

Strombolian explosions have a greater complexity compared to simple bursting of an overpressurized slug (Gaudin et al., 2014, 2017; Johnson & Lees, 2000; Lyons et al., 2012; Taddeucci et al., 2012). For example, two distinct behaviors have recently been observed at Santiaguito Volcano (Guatemala), one characterized by passive degassing linked to slow inflation and the other by explosive events linked to fast inflation associated with VLPs (Johnson et al., 2014). The degassing behavior type affected within a short time the deformation of the volcanic edifice as well as the explosion intensity. The alternation between passive degassing and explosive behavior has also been observed at Stromboli Volcano, where it has been linked to the different level of overpressure of the ascending slug (Del Bello et al., 2012). The overpressure of the slug during its ascent is related to the equilibrium of magma-static, viscous, and inertial forces according to the Rayleigh-Plesset equation (Plesset & Prosperetti, 1977). James et al. (2009) provided a qualitative correlation between overpressure (expressed by geophysical properties such as pressure transients and acoustic signals) and the magnitude and eruption style.

Despite the large extent of geophysical records, currently, the phenomena related to gas slug ascent cannot be observed directly. Indirect measurements of source dynamics, such as seismicity and/or ground tilt, have been complemented by more recent methodologies such as microgravity techniques, which have provided useful information for imaging underground processes (Carbone et al., 2015; Carbone et al., 2017). Nevertheless, the application of microgravity techniques is still limited due to high instrument costs and lack of adequate equipment robust enough to be deployed in noisy and harsh volcanic environments. As a result, the study of slug dynamics in volcanic systems is based on numerical simulations and analogue modeling. For example, early slug ascent experiments in circular conduits focused on how the velocity of so-called long bubbles moving in a closed tube is affected by viscosity and surface tension (Zukoski, 1966). The impact of cylindrical boundaries on the ascent of large bubbles was analyzed by Collins (1967), while White and Beardmore (1962) studied the behavior of inviscid bubbles in tubes and their terminal velocity. More recently, Nogueira et al. (2003) applied a combination of particle image velocimetry (PIV) and pulsed shadowgraphy to characterize the flow around gas slugs and determined the velocity profiles in the liquid around and ahead of the bubble, its shape, and the shear stress profiles in the liquid surrounding the slug. In a subsequent study, the same authors presented the modeling of the flow in the wake of the gas slug (Nogueira, Riethmuller, et al., 2006), while its pattern was quantified by Campos and De Carvalho (1988).

Other experimental studies modeled the slug behavior in volcanic environments. Del Bello et al. (2012) presented the validation of theoretical models relating the thickness of the magma film descending around the slug to the overpressure during the slug’s ascent and the subsequent eruption explosivity. Physical experiments have also been used to model VLP-like signals related to gas slug ascent in conduits with a variable diameter (James et al., 2004; James et al., 2006), showing that pressure transients and flow dynamics could be responsible for the VLP signals.

On the numerical side, O’Brien and Bean (2008) investigated the relationship between seismicity and slugs ascending in the conduit, confirming that gas slug ascent can produce VLP-like signals. Araújo et al. (2012) investigated the dynamics of slugs rising through stagnant liquids in conduits with different diameters and in liquid with different viscosities.

In spite of the extensive studies aiming for a broader understanding of slug flow in conduits and the development of advanced experimental techniques (e.g., PIV), little has been done to investigate the coupling between the dynamics of the slugs and the elastic deformation of the surrounding medium. While James et al. (2008) hypothesized that the pressure and forces acting on the conduit wall due to slug ascent cause the conduit to experience dilation at the slug nose and compression at the slug base, their numerical model neglected any solid deformation, as the authors assumed that a rigid conduit reasonably simulated near-surface two-phase scenarios. Building on the hypothesis of conduit elasticity, Kawaguchi and Nishimura (2015) numerically modeled conduit deformation, showing a link between the dynamic of slugs and the tilt signal measured at the surface. However, they did not take into account the countereffect of the wall deformation on the dynamics of the slug.
The possibility of conduit deformation even in its shallow portion can further be supported by recent findings showing that fractures and high temperature can reduce rock-mass strength. Variations in rock-mass elastic modulus can range greatly from <1 GPa to (for more competent rocks) >40 GPa (e.g., Dzurisin, 2006 p. 281; Heap et al., 2009; Rocchi et al., 2004; Villeneuve et al., 2018). Experimental results on samples from Etna and Vesuvius (Rocchi et al., 2004) show that rock strength decreases to 10% of the initial values at 800 °C to 900 °C. The combination of high temperature and rock cracks and porosity highlights the potential for soft, deformable, elastic conduits in shallower portions of volcanic edifices.

Here, we propose an analogue model of a slug rising within an elastic conduit and analyze the interaction between the flow in the conduit and the displacement of the surrounding medium using PIV and image processing techniques. We investigate the transition between two different slug regimes: “regular slugs” and “super slugs.” We hypothesize that these very large slugs may be responsible for the most energetic Strombolian eruptions.

2. Materials and Methods

2.1. Scaling of the Analogue Models

We conducted a series of experiments to simulate a two-phase flow regime known as “gas slug” typically associated with Strombolian eruptions. The gas slug condition represents a two-phase flow where large bubbles, with diameters approaching that of the conduit and lengths at least two times larger than the conduit diameter, rise within a continuous liquid phase. As a convention, we adopted the terminology commonly used in volcanology in which the gas phase is referred to as the slug (e.g., Clift et al., 1978; James et al., 2004; Jaupart & Vergniolle, 1989; Ripepe et al., 2001; Seyfried & Freundt, 2000). The analogue approach has been used in several studies applied to basaltic volcanoes (James et al., 2004, 2006, 2008, 2009; Jaupart & Vergniolle, 1988, 1989; Seyfried & Freundt, 2000, Del Bello et al., 2012, Del Bello et al., 2015; Capponi et al., 2016, 2017; Pering et al., 2017), providing useful insights into first-order conduit dynamics that are not accessible with other methods of investigation. The experiments that we conducted are designed to simulate a range of different scenarios that can be compared to medium-/low-viscosity magmatic systems.

The bubble dynamics depends on physical and geometrical properties of the conduit system such as the viscosity ($\mu$), the density ($\rho$) and surface tension ($\gamma$) of the liquid filling the conduit, the gravitational acceleration ($g$), and the diameter of the conduit (D). These quantities are combined into various dimensionless numbers to scale slugs simulated in the laboratory to the natural conditions (Seyfried & Freundt, 2000; Wallis, 1969; White & Beardmore, 1962).

The Froude number is related to the balance between inertia and gravity and is defined as

$$Fr = \frac{V_b}{\sqrt{gD}},$$

where $V_b$ represents the theoretical ascent velocity of the slug, derived by Goldsmith and Mason (1962) and extended by Brown (1965), to account for the relationship between the ascent velocity and the thickness of the falling film $\lambda$:

$$V_b = \frac{2\rho \lambda^2}{3\mu(r_c - \lambda)}.$$  \hspace{1cm} (2)

The Morton number reflects the balance between viscosity and surface tension, expressed as

$$Mo = \frac{g\mu^4}{\rho\gamma^3},$$

and the Eötvös number is a measure of the balance between gravity and surface tension:

$$Eo = \frac{\rho g D^2}{\gamma}.$$  \hspace{1cm} (4)

The dimensionless inverse viscosity is
We refer to $V_{\text{obs}}$ as the observed ascending slug velocity, to differentiate it from the theoretical velocity $V_b$ that is based on a rigid conduit model (equation (2)).

According to equation (4), the diameter of the conduit strongly controls the Eötvös number, and at our laboratory scale, the conduit produces a much smaller Eötvös number compared to low-viscosity magmatic systems, potentially enhancing the effects of the surface tension. However, it has been shown that for $Mo > 10^6$ and $Eo > 40$, surface tension does not significantly affect the slug ascent and therefore the difference is not considered as a controlling factor (Llewellyn et al., 2011; Seyfried & Freundt, 2000; Viana et al., 2003). Further, the inverse viscosity spans regimes for both viscous control ($N_f < 2$) and for an inviscid approximation not considered as a controlling factor (Llewellyn et al., 2011; Seyfried & Freundt, 2000). These ranges consider an ascent within inertial and transitional regimes, for which the velocity depends on slug buoyancy and liquid viscosity (White & Beardmore, 1962). For our study, we considered $0.015 < D < 0.025$ m, $0.001 < \mu < 1$ Pa·s, and $970 < \rho < 998$ kg·m⁻³ and $0.025 < \gamma < 0.073$ N·m⁻¹, $0.034 < Fr < 0.34$, $30 < Eo < 237$, $10^{13} < Mo < 10^7$, and $3 < N_f < 12355$ (Table 1). The range of slug velocity observed in our experiments is $0.006 < V_{\text{obs}} < 1$ m·s⁻¹.

Gelatin has been shown to be a good analogue for the shallow Earth’s crust (Di Giuseppe et al., 2009). Indeed, gelatin shows a variable behavior depending on its state (elastic to viscoelastic rheology in the solid one and viscous rheology in the non-solid one), composition, concentration, temperature, ageing, and the applied strain rate (Barrangou et al., 2006; Bot et al., 1996a, 1996b; Kavanagh et al., 2013; Kavanagh & Ross-Murphy, 1998; Norziah et al., 2006). Gelatin is often used as rock analogue to study shallow crustal processes, especially propagation of dykes (Heimpel & Olson, 1994; Muller et al., 2001; Pansino et al., 2019; Pansino & Taisne, 2019; Rivalta et al., 2005; Takada, 1990) as it can scale to the Earth’s crust. It has also been used to simulate the volcanic edifice (Acocella & Tibaldi, 2005; Walter & Troll, 2003).

At the time scale of our experiments, we considered the gelatin to be an ideal elastic medium in the solid state, and therefore

$$\sigma = E \cdot \varepsilon,$$

where $\sigma$ is stress, $E$ is the solid Young’s modulus, and $\varepsilon$ is the strain (Hooke’s law). The characteristics of this state of the gelatin are assumed to be representative of the elastic way the Earth’s upper crust behaves in presence of instantaneously applied stress (Ranalli, 1995). Following Pansino and Taisne (2019), we measured the shear modulus before each experiment, which was consistent across experiments. An average value of 5000 Pa is used in this study. To represent the observed conduit deformation, we define the dimensionless parameter, $b^*$, which represents the deformation as the ratio between the conduit wall displacement $b$ and the undeformed conduit radius $r_c$. We assume that the elasticity of the gelatin and the scale of deformation observed in our experiments are comparable with those of a shallow sustained conduit in a natural volcanic system, where the high temperature and the low competence of the materials can justify a low shear modulus of the surrounding rocks.

Finally, the gelatin had a concentration of 3.75 wt% and a measured density of ~1010 kg·m⁻³, which leads to a density ratio of 1.01 between gelatin and water and 1.04 between gelatin and silicon oil. These values are similar to the one of host rock/magma so that the experiment allows the scaling of the natural phenomena (Acocella & Tibaldi, 2005).

### Table 1

Table 1: Dimensionless Parameters for Experimental Conditions Representing a Basaltic Conduit and Volcanic Slugs Calculated Assuming Typical Strombolian’s Parameters.

| Symbol (unit) | Laboratory scale | Volcano scale |
|---------------|------------------|--------------|
| $\mu$ (Pa·s)  | 0.0012           | 10⁻⁵        |
| $\rho$ (kg·m⁻³) | 999.7            | 970          |
| $\gamma$ (N·m⁻¹) | 0.073            | 0.025        |
| Mo            | 2.5 10¹¹        | 647.3        |
| Eo            | 30–83           | 38–237       |
| $N_f$         | 5742–12355     | 3–12         |
| Fr            | 0.34            | 0.03–0.109   |

For low-viscosity magmatic systems, the typical range of these parameters are as follows: $0.1 < Fr < 0.35$, $10^2 < Eo < 10^7$, $10^2 < Mo < 10^6$, and $2.1 < N_f < 1.2 10^6$, assuming $10 < \mu < 10^5$ Pa·s, $\rho = 2600$ kg·m⁻³, and $\gamma = 0.4$ N·m⁻¹ for basalt and $1 < D < 10$ m for the conduit (Seyfried & Freundt, 2000). These ranges consider an ascent within inertial and transitional regimes, for which the velocity depends on slug buoyancy and liquid viscosity (White & Beardmore, 1962). For our study, we considered $0.015 < D < 0.025$ m, $0.001 < \mu < 1$ Pa·s, and $970 < \rho < 998$ kg·m⁻³ and $0.025 < \gamma < 0.073$ N·m⁻¹, $0.034 < Fr < 0.34$, $30 < Eo < 237$, $10^{13} < Mo < 10^7$, and $3 < N_f < 12355$ (Table 1). The range of slug velocity observed in our experiments is $0.006 < V_{\text{obs}} < 1$ m·s⁻¹.
2.2. Experimental Setup

To represent the interaction between bubbles rising within the conduit and the volcanic edifice that surround it, we had to develop an apparatus that allowed the full coupling between fluid and solid phase. To this end, we conducted experiments using gelatin to simulate the volcanic rock pile and an experimental trick for a conduit within it. This allows for a full coupling between the magma and wall analogues as no barrier between the solid gelatin and the fluid within the conduit was used.

The tank is composed of two sections as shown in Figure 1a: A narrow lower portion (base: 25 cm x 25 cm, height: 70 cm) and a wide upper portion (base: 80 cm x 80 cm, height: 30 cm). This geometry is chosen to reduce the wall effect in the uppermost portion of the gelatin and consequently reduce biases (side effects) in the recorded deformation data. The bottom part of the tank is connected to a removable reservoir, which stored the air used to generate the slugs. The gelatin (250 bloom, industrial grade gelatin) was prepared by mixing gelatin powder with hot water (60 °C), to dissolve the solid gelatin. Subsequently, a thin layer of oil was added on top of the gelatin to prevent evaporation during the cooling phase in a cold room at 15 °C for 48 h that allowed its solidification.

In order to obtain a smooth and continuous conduit from the base of the tank to the top free surface, we designed a simple mechanical apparatus to cast the conduit in the gelatin without damaging it. During the preparation phase of the experiment (Figure 1a), a rigid vertical rod was introduced into the cooling gelatin. The constant motion of the rod prevented the gelatin from solidifying at the rod/gelatin interface and decreased the chances of developing discontinuities at the conduit wall. To maintain the rod in motion until the complete solidification of the gelatin, we designed and developed a motorized device. It consisted of a linear actuator, of which a motor control board was connected to an Arduino board, a programmable microcontroller extensively used in robotics engineer to control different technologies via a centralized system. This configuration was used to control the frequency and amplitude of the rod displacements (see the upper panel in Figure 1a). Once the gelatin solidified, the rod was extracted. During this phase, the rod was heated up circulating water in the inside to further reduce the cohesion at the interface and slowly pulled out of the gelatin. At the same time, the hollow cylindrical space left by the rod was filled with a fluid representing the magma analogues, water, and silicon oil, chosen to explore a range of viscosity between $10^{-3}$ and 1 Pa·s.

At the bottom of the tank, we designed a small chamber with an air trap which can be controlled from the outside to generate the slugs. To fulfill the principle of mass and volume conservation, the air trap was
charged before the experiments in order not to affect the initial volume (Figure 1b) and to prevent fluid motion into the conduit before slugs are released.

The images were recorded with a Canon EOS 1200D at 24 and 50 frames per second (fps) and Phantom Miro M120 at 100 and 200 fps. The field of view was illuminated by a laser light sheet, which was produced with a combination of laser pointers and cylindrical solid glass rods. The glass rods transformed the beam into a sheet with less than 1-mm thickness illuminating the region of interest. To visualize and acquire deformation data, we applied particle image velocimetry (PIV) and image processing techniques to detect the strain in the region around the conduit. These methods are both nonintrusive and can provide quantitative data on the velocity field within the conduit and displacement in the surrounding gelatin when bubbles are ascending (Figure 1c).

Polyamide particles with diameter of 100 μm and specific density of 1.2 g/cm³ were used as seeding particles to visualize the flow dynamics in the conduit and track the deformations in the gelatin. The seeding particles were added to the liquid gelatin before solidification and were only distributed in the sheet in the central x-y plane of the tank crossing the conduit. This would enhance the visibility of the deformations and the quality of measurements. Particles of the same size but at higher concentration were added to the fluid in the conduit in order to visualize and measure the flow dynamics during the bubble rise. Figure 2 illustrates raw images of the analogue crust and magma with the seeding particles.

The raw images were preprocessed, and PIV analyses were carried out by the commercial software DaVis 10 (product of Lavision www.lavision.de). PIV analysis can provide the instantaneous velocity field and displacements in the conduit and the surrounding solid gelatin, respectively. The software analyzes the position of the seeding particles at discrete time instants by cross-correlation and provides two-dimensional velocity data on a planar domain. The observation area was divided by 64 × 64 pixels and subsequently by 32 × 32 interrogation areas, and the average motion of particles was studied. The determination of the average particle displacement was also accomplished by computing the spatial cross-correlation of the particle images.

Table 2 presents a summary of experimental conditions including the size of the observation area, sampling rate, size of the conduit and the physical properties of the fluid, and the solid medium analogues of the magma and the elastic crust.

### 2.3. Slug Flow Simulation

Slugs of air are released from a reservoir located at the base of the tank, which is also linked to the conduit to simulate a typical Strombolian activity. To meet the principle of mass conservation, the air is stored within the conduit system before running the simulations. Injection of gas from an external source may produce misleading deformation signals due to the increase of pressure in the conduit. To avoid this issue, we...
designed a special reservoir equipped with a “gas trap” previously charged with air that it is in contact with the liquid phase constituting the magma analogue (Figure 1b). The trap was dome-shaped and had a volume of 70 cm³. By rotating the handle, a part of the air pocket is gradually released forming a bubble, which depends on the amount of time the trap is open. The bubble is driven by the buoyancy to the conduit where it begins to rise toward the surface. The limited volume of the gas trap determines the number of slugs that can be released during the experiment. The trap is then recharged in between experiments to restore the initial volume condition. While this setup does not allow a precise control over the volume of gas released for each slug, this parameter could be measured from the video recorded during the experiment. We identified frames containing clear images of the slugs, and we analyzed them with the image processing toolbox available in Matlab. We extracted the boundaries' coordinates which were fitted by a polynomial function used to compute the volume by disk integration. Slug volumes ranged from 3 to 21 cm³. Length and volume of the slugs are measured both on the upper and lower sections of the conduit according to the laser/cameras configuration used in the experiments (Figure 1).

3. Results and Discussion

The shape of slugs rising in rigid conduits is known to be controlled by variations in fluid viscosity, surface tension, and buoyancy forces. A slug can form a bullet-like shape (Figure 3a) with a flat tail when rising within a low viscosity fluid and a hemispheric concave shape (Figure 3b) when ascending within a high-viscosity fluid (Campos & Guedes de Carvalho, 1988). Besides the bullet-like geometry, which is widely described in the literature (i.e., Morgado et al., 2016, review paper), in our experiment, we observed another slug shape which we here term as a “super slug.” Super slugs have a larger head and taper toward the tail (Figure 3c). In silicon oil, this shape is more pronounced, presenting a streamlined body (Figure 3d). Indeed, bubbles narrowing toward the tail, so-called cusped-tail bubbles, have been observed before in non-Newtonian fluids (Chhabra, 2006; Divoux et al., 2008; Divoux et al., 2009; Hassager, 1979; Liu et al., 1995; Sousa et al., 2004), with this cusped shape being a function of the concentration of the gel-based fluid and the bubble volume. In comparison, in our experiments, the viscous fluids were Newtonian, so the streamlined bubble bodies we observed can be attributed to changes of slug dynamics induced by the deformation of the elastic conduit rather than for non-Newtonian rheological properties of the fluid.

The slug shape variation with volume in our experiments is shown in Figure 4 for both silicon oil and water. In silicon oil, the slug shape becomes more streamlined, eventually evolving into a super slug (Figures 4a and 4b). At the same time, the larger volume and streamlined shape allow the super slug to reach a higher rising velocity ($V_{\text{obs}}$) compared to a theoretical slug velocity ($V_{\text{b}}$), thus inducing deformation of the conduit wall $b$ by up to 50% of its original diameter ($b^* = 0.5$). In water, the tapered shape is not as pronounced and is only prominent for large volumes of gas (Figures 4c and 4d). The slug velocity is similar to the theoretical one. The deformation of the conduit wall is smaller and independent of the slug size, with a maximum deformation of the conduit of around 10% of its original diameter ($b^* = 0.1$).

Differences in the stress and strain pattern between slugs rising in silicon oil and water are also visible using polarized film. The gelatin is photoelastic, allowing visualization of stress patterns as fringes of color. This

Table 2
Summary of Tests, Observation Areas, and Physical Properties of Gelatin.

| Test No | Configuration Sampling rate (fps) | Size of the observation field | Conduit diameter | Fluid medium | Physical properties | μ (Pa·s) | ρ (kgm⁻³) | γ (N·m⁻¹) |
|--------|---------------------------------|-------------------------------|-----------------|--------------|---------------------|---------|----------|----------|
| 1      | 2                               | 24                            | 31 x 20         | 2.5          | Oil1                | 1       | 970      | 0.025    |
| 2a     | 2                               | 24                            | 14 x 11         | 2.5          | Water               | 0.001   | 998      | 0.073    |
| 2b     | 2                               | 50                            | 25 x 20         | 2.5          | Liquid gelatin      | 0.001   | 1000     | 0.073    |
| 3      | 2                               | 100–200                       | 25 x 20         | 1.5          | Oil1                | 1       | 970      | 0.025    |
| 4      | 1                               | 100                           | 25 x 20         | 1.5          | Oil1                | 1       | 970      | 0.025    |
| 5      | 1                               | 100                           | 25 x 20         | 1.5          | Oil1                | 1       | 970      | 0.025    |
| 6      | 1                               | 100–200                       | 25 x 20         | 2.5          | Oil1                | 1       | 970      | 0.025    |
| 7      | 1                               | 200                           | 25 x 20         | 2.5          | Oil2                | 0.5     | 970      | 0.025    |
| 8      | 1                               | 200                           | 25 x 20         | 2.5          | Water               | 0.001   | 998      | 0.073    |
technique allows a first qualitative estimate of the stress field surrounding the slug, but does not allow to quantitatively estimate the stress. Figure 5 shows differences in the stress pattern between “super slugs” and “regular slugs.” For slugs in silicon oil (a and b), an important stress region is visible above the head of the slug which appears to be related to the conduit geometry, smaller for a narrower conduit, as highlighted by a dimmer intensity of the colors. For slugs rising in water, the stress region is almost absent (c), suggesting a smaller deformation of the conduit wall. As a first assumption, super slugs form when the conduit walls stretch as a consequence of larger forces acting on the conduit wall, a situation that allows a more efficient return flow.

We speculate that the super slug state is related to the deformation of the conduit, which in turn occurs as the liquid film around the slug accelerates due to the Bernoulli effect. According to Bernoulli’s equation, the reduction of the conduit diameter causes the fluid to move faster, which decreases the pressure compared to the regions where the diameter is larger and where the fluid is moving more slowly, leading to a pressure increase. For experiments conducted in silicon oil, the Bernoulli effect becomes more evident as a result of higher viscous forces that counteract the strong buoyancy of the bubble: When the slug is squished, an increasing downward flow around the slug applies larger shear stress and pressure on the conduit wall, amplifying the conduit deformation. If the volume and mass of the slug are bigger than a threshold, the slug deforms the conduit, becomes a super slug, and accelerates. Figure 6 depicts the relationship between the normalized slug velocity (which is equal to the ratio between the observed velocity \( V_{\text{obs}} \) and the theoretical velocity \( V_b \)) and the normalized length of the slug (which is equal to the ratio of the length \( L_b \) divided by the diameter of the conduit \( D_c \)). In experiments with water, slug velocity is slightly affected by the bubble size. In contrast, experiments with silicon oil suggest that slug velocity is proportional to the bubble length. This contrast is also visible in Figure 6, where the observed slug velocity \( V_{\text{obs}} \) diverges from the theoretical velocity \( V_b \) for \( b^* \) greater than 0.1. As noted before, smaller slugs are usually bullet

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**Figure 3.** Comparison between shapes of slugs rising into different media, water and oil in relation to rigid conduits (a) (b), and elastic conduits (c) (d). In red are represented the contour of the deformed conduits. \( D_1 \) and \( D_2 \) indicate the conduit diameter above and below the slug, respectively.
shaped (Araújo et al., 2012), and their velocity is therefore strongly dependent both on the radius of the conduit $r_c$ and the thickness of the liquid film $\lambda$, which are both assumed constant. This assumption makes equation (2) unsuitable for determining the velocity of super slugs, because their diameter and the thickness of the liquid film around them are not constant.

Figure 4. Shape variation of slugs for different values of viscosity of the fluid in conduits of different diameters: (a) Slugs rising in silicon oil (viscosity = 1 Pa·s) in a smaller diameter conduit ($D = 0.015$ m), (b) Slugs rising in silicon oil (viscosity = 1 Pa·s) in a bigger diameter conduit ($D = 0.025$ m), (c) Slugs rising in water (viscosity = 0.001 Pa·s) in a smaller diameter conduit ($D = 0.015$ m), and (d) Slugs rising in water (viscosity = 0.001 Pa·s) in a bigger diameter conduit ($D = 0.025$ m). The shape of the slug changes as a function of the volume, evolving into a streamlined body shape for relatively large volumes of gas in silicon oil.
Based on these aforementioned observations, we have identified two slug types: The regular slug is smaller and follows the dynamics and shape of the bullet-shaped slug; the super slug has a larger volume, its shape tapers toward the tail, and its higher rising velocity cannot be explained with equation (2). We believe that the different behavior associated with the two slug types can be linked to important variation of the pressure gradient and shear stress in the slug region. Regular slugs contain smaller volumes of gas, rise in the conduit in equilibrium, and induce small deformations of the conduit. Super slugs contain larger gas volumes, perturb the stress field, and generate a larger deformation of the conduit wall.

These behaviors observed in our experiments agree with behaviors observed in natural systems: Burst overpressure values in the range between 0.1 to 0.5 MPa are linked to mildly explosive Strombolian events (Harris & Ripepe, 2007; Ripepe et al., 2002), while burst overpressure of up to 4 MPa corresponds to violent explosive events (Ripepe & Marchetti, 2002; Vergniolle et al., 1996).

The analysis of the displacement within the surrounding medium performed with the PIV technique allowed us to observe, for the first time, the displacement pattern previously hypothesized on the basis of pressure observation in rigid conduits and numerical approaches (Figure 7). The displacement pattern revealed two main stress regions: One located above the slug, where the stress due to the rise of the slug is widening the conduit diameter (D_1 > D); and a second one below the slug, where the conduit diameter is narrowing (D_2 < D) due to the reduction of fluid pressure filling the conduit (Figures 3c and 3d). The region of the conduit occupied by the slug can therefore be considered as a transition zone between the wider and narrower conduit diameters. In this transition region, as...
shown in Figure 7, the displacement affects a very narrow section of the conduit. Interestingly, in silicon oil experiments, we observe that the thickness of the liquid film around super slugs is not constant as is the case for regular slugs and in addition increases toward the tail of the slugs.

Shear stress and pressure acting on the conduit during the slug's ascent lead to dilation above the slug and contraction below the slug (James et al., 2008). In our experiments, the conduit deformation we observe is mainly linked to the shear stress (implied by gelatin displacement) acting on the conduit wall and small pressure variation attributed to the fluid motion, since decompression is absent, owing to the scale and length of our model conduit (i.e., slugs do not expand as they rise in the conduit).

Figure 7 also shows the link between the size of the slug and displacement magnitude. For a 14-cm slug, the displacement reached 7 mm, while for a 3-cm slug, the displacement was 0.1 mm.

In addition to using the PIV technique to measure deformation, the technique also allowed us to analyze the liquid flow within the conduit and around the slugs (Figure 8). Interestingly, we found that for a super slug, there is a region of very high upward velocity immediately above the slug's head, while for a regular slug, the liquid column above the slug moves upward at a lower velocity, causing a gradual upward motion of the free liquid surface (Videos V01 and V02). Previously, the acceleration of the slug head has been attributed to its expansion (James et al., 2008). As mentioned above, in our experiments, no slug expansion has been observed, meaning that the high upward velocity observed in the fluid above the super slug’s head is linked to the slug’s acceleration. Furthermore, our results show that also the viscosity controls the extent of the liquid flow field ahead of the rising slug, with a greater fluid region affected at low viscosity. This agrees with Nogueira, Riethmuler et al. (2006), who observes that the presence of the slug is “felt” some distance ahead of its head. This distance is slightly larger for decreasing liquid viscosities, suggesting that the presence of the bubble affects a larger area, as the inertial forces are higher relative to the viscous ones. In our experiments,
we observe that the extent of this region is also controlled by the size of the slug: A smaller area for super slugs compared to the one produced by normal slugs. As a consequence of bubble size and viscosity, we observed a gradual upward movement of the liquid-free surface during the ascent of regular slugs, while for ascending super slugs, the liquid-free surface does not rise initially and dramatically accelerates upward only when the slug is approaching the surface (see Videos V01 and V02 in the supplementary material). Our observations are similar observations in the natural system, where different uplift patterns are linked to explosive and passive degassing. For instance, rapid inflation rates of the dome surface at Santiaguito Volcano (Guatemala) are linked to explosive events that generate very long period (VLP) earthquakes, and less rapid inflation episodes are linked to passive degassing events that do not generate VLPs (Johnson et al., 2014). Figure 8 compares the flow profiles generated by a super slug and a regular slug. We hypothesize that the observed high-velocity region above the heads of super slugs can be directly related overpressure within the slug, while regular slugs, which do not show a high-velocity region, may rise at pressure equilibrium. This hypothesis is in line with the modeling results of Del Bello et al. (2012), which link the overpressure to the gas volume and the thickness of the film of magma descending around the slug.

To relate the velocity measured in our experiments within the liquid column with the overpressure observed in natural systems, we used the drag force equation:

$$F_D = \left(\frac{1}{2} \rho V_b^2\right) C_D \pi r_b^2,$$ (7)

where $C_D$ is the drag coefficient, which depends on the shape of the slug and on the Reynolds number, and the term in brackets corresponds to dynamic pressure. (Note that here following equation (2), we assume that if the radius of a slug increases compared to its initial value as a consequence of conduit deformation, its rising velocity also increases.) Therefore, based on equation 7, the drag force acting on the slug also
increases, in turn increasing the dynamic pressure at the head of the slug. On the other hand, the drag coefficient $C_D$ decreases due to the tapering toward the tail of the super slug, thus dampening the effect of the increasing velocity and radius. Nevertheless, because of the square factor in both the velocity and the slug radius, we can assume that in equation 7, the drag coefficient variation becomes negligible. However, further work will be necessary to investigate the relationship between the slug’s inner pressure and the controlling parameters.

4. Conclusions

This work presents a series of analogue experiments mimicking the dynamics of slugs rising in an elastic deformable volcanic conduit. For the first time, elastic conduit deformation was analyzed by applying the PIV technique to measure both displacements in the fluid and the surrounding elastic medium. We have observed super slugs, which are characterized by a tapered shape and a higher rising velocity compared to regular slugs. Interestingly, we have found that the dynamics of the two slug types affects conduit wall displacement. While regular slugs have a low velocity and rise at pressure equilibrium, causing very little or no conduit wall deformation, super slugs rise at a high velocity and cause significant deformation of the conduit, which might explain the generation of more energetic explosions at the surface, and will be subject of future studies. Within our analogue conduit, we have observed and quantified three different regions: Dilation above the slug; a transitional region along the slug where shear stress is more dominant; and contraction below the slug. The presence of these three regions has been previously only hypothesized and numerically modeled. Here, for the first time, we have observed and measured it.

Moreover, we have identified similarities between the acceleration patterns of the liquid-free surface in our experiments and dome uplift observed in natural systems. While rapid inflation rates of the dome surface are linked to explosive events, less rapid inflation episodes are linked to passive degassing events. These observations could be key not only to discriminating explosive events from passive degassing but also potentially to forecasting explosive styles. Further work is necessary to define the threshold that mark the transition between regular slug and super slug; this information will be important for the development of a theoretical formulation that can describe the dynamics of the observed super slugs, with implications to volcano monitoring.

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