Waves of bubbles in basaltic magmas and lavas

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Abstract. Initially homogeneous suspensions of bubbles in basaltic magmas and lava flows may become unstable and form rising waves or layers of bubbles. We derive a set of model equations for the two-phase (bubble-liquid) system and present the results of a linear stability analysis and numerical simulations. Periodic vesicle layers are preserved in Columbia River flows with a spacing of ~1 m; the prediction of the stability analysis combined with a simple model for solidification of the lava suggests that vesicle layers may represent waves of bubbles formed within the flow. The spacing of layers is determined by a balance between the growth of bubbles and hydrodynamic self-diffusion. Vesicular layers preserved in Columbia River flows may thus form by hydrodynamic processes and do not require the repeated injection of fresh volatile-rich magma or a periodic nucleation of bubbles. Waves of bubbles may also develop in magma chambers and conduits and could play a role in eruption dynamics.

Introduction

The size, shape, concentration, and distribution of vesicles preserved in solidified lava flows depends on dynamical, thermal, and physicochemical processes occurring within the lava. Thus the measurement of vesicle characteristics combined with models of bubble behavior can provide information about the dynamics of lava flows [e.g., Walker, 1989], history of flow emplacement [Aubele et al., 1988; Sahagian et al., 1989; Cashman et al., 1994], and various eruption processes [Mangan et al., 1993] for both active and prehistoric flows.

A number of specific problems have been addressed by studying bubbles in active flows and vesicles preserved in solidified lavas. Since the shape of bubbles depends on the local strain rate [e.g., Stein and Spera, 1992; Stone, 1994], the measured shape of vesicles provides constraints on lava viscosity and flow rate [e.g., M. Polacci and P. Papale, The evolution of lava flows from ephemeral vents at Mount Etna: Insights from vesicle distribution and morphological studies, submitted to Journal of Volcanology and Geothermal Research, 1996]. The size distribution of bubbles can be used to estimate nucleation, growth, and coalescence rates of bubbles in erupting magmas [e.g., Toramaru, 1990, 1995; Mangan et al., 1993] and active lava flows [e.g., Cashman et al., 1994]. The spatial and size distribution of vesicles preserved in solidified lava flows depends on the rise speed and rate of coalescence of bubbles, which in turn depends on the growth rate of bubbles and the viscosity of the surrounding magma [e.g., Sahagian, 1985; Aubele et al., 1988]. Sahagian et al. [1989] and Sahagian and Maus [1994] have also suggested that the preserved distribution of bubbles may be used to infer paleoellevation and/or paleoatmospheric pressure.

In this paper, we consider the dynamics of bubbles rising in an otherwise quiescent basaltic lava flow. Previous studies have generally found a good agreement between model calculations and observations. For example, Aubele et al. [1988] compared measured bubble distributions from thin (<10 m thick) flows in New Mexico with calculations which account for the temperature-dependence of viscosity; Sahagian and coworkers include a model for bubble coalescence [Sahagian, 1985] and also find good agreement between model predictions and observations for thin flows from California [Sahagian et al., 1989] and Hawaii [Sahagian and Maus, 1994]. Here we focus on the effects of the interaction between bubbles which have been ignored in these previous studies. We show that bubble interactions will affect the distribution of bubbles and that an instability can develop which leads to the formation of layered vesicular structures.

Vesicle Layers in Columbia River Flows

Within thick Columbia River lava flows, two distinct vesicular regions are often observed [McMillan et al., 1987], as illustrated in Figure 1a. The vesicular region near the top of the flows is thought to form shortly after the emplacement of the lavas and to preserve bubbles nucleated during ascent and eruption. At a depth of about 40% of the flow thickness, there is often a second vesicular zone. The "internal" vesicular region is thought to contain bubbles nucleated at the lower so-
solidification front, which rise through the lava and are trapped beneath the downward-migrating upper solidification front [McMillan et al., 1987].

The internal vesicular region, as illustrated in Figure 1b, often contains regularly spaced vesicular layers which appear to be horizontally continuous. McMillan et al. [1989] proposed that the layering results from a cyclic enrichment and depletion of the vapor phase so that the nucleation of bubbles also occurs cyclically. A similar idea involving oscillatory nucleation about a binary eutectic is sometimes proposed as the mechanism for forming layers of crystals in large intrusive magmatic bodies; numerical studies confirm that layered structures can be formed by such a mechanism [Holt et al., 1993]. However, it is unclear why a periodic enrichment and depletion of the vapor phase would occur for bubbles in magmatic systems.

An alternative explanation is that the Columbia flows are inflated flows and that a new vesicle layer is produced by each injection. Other long basaltic flows, such as the 75-km-long and 10 to 15-m-thick Carriozo flow in New Mexico, are known to be inflated [Keszthelyi and Pieri, 1993]. However, there are apparently no textural and composition changes within the internal vesicular zone [McMillan et al., 1989]. In addition, the presence of a small number of very large bubbles (radii greater than a few centimeters) implies significant coalescence of bubbles [McMillan et al., 1987]. Growth of bubbles by coalescence occurs as bubbles overtake and merge with smaller bubbles, which requires that the bubbles rise and interact over a distance of at least several meters [e.g., Sahagian, 1985; Manga and Stone, 1994].

Here we propose that the layering of vesicles can develop as the bubbles rise from a wave-like instability and demonstrate that a suitable set of model equations can explain the observed spacing of the layers. While the model studied here is greatly simplified and many of the physical properties of the bubble-magma system are not very accurately known, the results suggest that such instabilities can occur and will affect the final distribution of vesicles preserved in lava flows.

A Simple Experimental Model

Waves of particle (or bubble) concentration occur in a wide range of mobile particulate (or bubbly) systems, including granular materials, fluidized beds, and suspensions [e.g., Joseph and Schaeffer, 1990; Hinch, 1995]. In order to illustrate physically the type of concentration waves that may form in magmatic systems, we present some observations that illustrate waves in bubbly fluids. In Figure 2 we show a photograph of a glass of Guinness beer a few seconds after the beer was poured. Initially, the bubbles are distributed nearly uniformly but quickly form layers or waves which appear to propagate downward. Between the layers are plume-like instabilities. This simple experiment works well with creamy beers on tap and Guinness from a can.

A simple physical explanation for the formation of concentration waves can be provided. The rise speed of bubbles decreases as the concentration of bubbles, \( \phi \), increases; this hindered motion is due primarily to the backflow between the bubbles, which is a consequence of conservation of mass. Consider a one-dimensional distribution of bubbles, illustrated in Figure 3, with a "layered" structure. Bubbles from the top of the layer rise more rapidly than bubbles in the center of the layer.
Figure 2. Bubbles in a glass of Guinness beer a few seconds after the beer was poured. The bubbles are initially homogeneously distributed. Horizontal and downward propagating layers of bubbles develop. Secondary Rayleigh-Taylor instabilities form from the layers.

and thus rise rapidly from the top of one layer to the bottom of the next layer. Even though the bubbles themselves are moving upward, the layered structure can thus propagate downward.

The demonstration in Figure 2 illustrates qualitatively the process we are studying but differs in some respects from bubbles in lavas. The Reynolds number, which represents the ratio of inertial to viscous forces,

$$R = \frac{\rho U_0 a}{\mu},$$  \hspace{1cm} (1)

is \(\sim 1\) in the experiment, whereas bubbles in lavas are generally characterized by \(R \ll 1\). Here \(\rho\) and \(\mu\) are the fluid density and viscosity, respectively, \(U_0\) is the bubble rise speed, and \(a\) is the bubble radius. In most mobile particulate systems, it is the inertia of the particles and fluid which allows the amplitude of the instability to grow. Nevertheless, the qualitative illustration of the propagation of waves shown in Figure 3 should still apply to the low Reynolds number limit.

Model

Here we study in more detail some of the processes that may lead to concentration waves in magmatic systems, analogous to those shown in Figure 2, for \(R \ll 1\). Since the theory and theoretical analysis of two-phase flows is very involved and in many aspects incomplete we will present the simplest "useful" analysis which illustrates the main features of the problem. Our approach is to derive an equation describing the evolution of bubble concentration from "first principles"; the analysis is distinct from previous studies, for example, Batchelor [1988], since inertial effects are not important and are neglected.

Consider a one-dimensional model for the distribution of bubbles. Three-dimensional effects are discussed later in the paper. The volume fraction or concentration of bubbles, \(\phi\), satisfies a conservation equation, also a kinematic wave equation,

$$\frac{\partial \phi}{\partial t} + \frac{\partial (U\phi)}{\partial z} = A,$$  \hspace{1cm} (2)
where \( t \) is time, \( z \) is the vertical direction, and \( A \) describes the growth rate of the bubbles. \( U = U(\phi) \) is the velocity of the bubbles, which is assumed to depend only on the local concentration of bubbles. Equation (2) is an averaged equation so that fluctuations in the velocity of individual bubbles are ignored. We will see later that such fluctuations play an important role in mobile particulate systems, even in one-dimensional models such as the one studied here. As first shown by Kynch [1952] for suspensions, if \( A = 0 \), vertical concentration variations will lead to the formation of concentration shocks (there will be a jump in concentration), but the maximum concentration will not change.

In magmas and lavas, bubbles grow by diffusion of gas into the bubbles, by expansion resulting from a decrease in hydrostatic pressure as the bubbles rise, and by coalescence. Assuming for now that bubbles grow by diffusion alone, i.e., \( a(t) = \kappa/(\kappa + \phi) \) [e.g., Sparks, 1978],

\[
A = \frac{\kappa}{\alpha^2} \phi \tag{3}
\]

where \( \kappa \) is the diffusivity of the relevant volatiles through the magma. For basaltic flows with thickness less than about 100 m, growth by diffusion will dominate [e.g., Aubele et al., 1988].

The function \( U(\phi) \) is known empirically for solid spherical particles for \( \mathcal{R} \ll 1 \) and is of the form

\[
U(\phi) = U_o \left( \frac{1}{1 + \phi} \right)^n, \tag{4}
\]

where \( n \approx 5 \) [e.g., Russell et al., 1989]. We will assume equation (4) is also a suitable approximation for bubbles. We choose \( n = 3 \) for a weaker concentration dependence. \( U_o \) is the rise speed of a single bubble in an unbounded fluid given by

\[
U_o = \frac{\Delta \rho g a^2}{3 \mu}, \tag{5}
\]

where \( \Delta \rho \) is the density difference between the liquid and the bubble.

In sedimenting suspensions, the interface between particle-rich and particle-free fluid sometimes broadens as the particles settle. This process is referred to as self-induced hydrodynamic diffusion and arises due to velocity fluctuations in the sedimentation speed of individual particles [see Davis [1996] for a review of recent work]. For Stokes flow of nonbrowian particles, velocity fluctuations are due to spatial and temporal variations of the local separation distance between particles. Ham and Homsy [1988] and Davis and Hasse [1988] found that for \( \mathcal{R} \ll 1 \), the diffusivity in sedimenting suspensions of nearly monodisperse, noncolloidal, rigid spheres is of the form \( \kappa a U_o \), with \( c \approx 5 \) for \( 0.02 < \phi < 0.15 \). Thus, accounting for self-diffusion, the conservation equation (2) becomes

\[
\frac{\partial \phi}{\partial t} + \frac{\partial}{\partial z} \left[ U_o \phi \left( \frac{1}{1+\phi} \right)^n \right] = c a U_o \frac{\partial^2 \phi}{\partial z^2} + \frac{\kappa}{\alpha^2} \phi. \tag{6}
\]

The diffusive term in equation (6) can be obtained if we assume the velocity of particles also depends on \( \partial \phi/\partial z \).

We have assumed that all the bubbles have the same size. In a polydisperse suspension, the appropriate equations involve replacing \( \phi \) by \( \sum_n \Delta n_i \alpha_i^2/3 \), where \( n_i \) is the number of bubbles with radius \( \alpha_i \) per unit volume. We then must solve a large number of nonlinear, coupled, and time-dependent equations for \( n_i \). However, the appropriate form of equation (4) and the hydrodynamic self-diffusivity \( \kappa a U_o \) are not known for polydisperse suspensions, so that solutions to the more complicated system of equations will not necessarily be more informative or realistic.

**Stability analysis**

Although equation (6) is nonlinear in \( \phi \), we will study some of its features by performing a linear stability analysis. We let

\[
\phi(t, z) = \phi_0 + \phi_1(t, z) \tag{7}
\]

where \( \phi_1 \) is a small disturbance and \( \phi_0 \) is a constant. We assume solutions of the form

\[
\phi_1(t, z) = e^{rt+ikz} \tag{8}
\]

where \( \sigma \) is the growth rate of the disturbance and \( k \) is the wavenumber of the disturbance. Linearizing equation (6) by assuming \( \phi \) is small so that \( 1/(1 + \phi) \approx 1 - \phi \), and keeping only terms of \( O(\epsilon) \), we obtain the dispersion relation

\[
\sigma = ik(2n\phi_0 - 1)U_o - k^2 \kappa a U_o + \frac{\kappa}{\alpha^2}. \tag{9}
\]

Equation (9) predicts that the fastest-growing wavelength is the longest wavelength \( (k = 0) \) and that the growth rate is independent of bubble concentration.

In the physical problem, most of the vesicularity preserved in the internal vesicular layers is thought to consist of bubbles which nucleate at the lower solidification front [McMillan et al., 1989]. Consequently, we expect the instability to develop once a sufficient vertical height of bubbles has formed. A more relevant problem is to determine the smallest wavelength which is unstable. Instability requires that the real part of \( \sigma \) is positive, thus wavelengths \( \lambda = 2\pi/k \) become unstable if

\[
\lambda > 2\pi \sqrt{\frac{5a^6 \Delta \rho g}{3 \kappa \mu c}}. \tag{10}
\]

We observe in equation (10) the very strong effect of bubble size on the wavelength of the instability. Equation (10) must also be subject to an additional constraint that

\[
\lambda \gg a \tag{11}
\]

since the physical processes of self-diffusion and the concentration dependence of the rise speed are macroscopic properties which apply over length scales much greater than the size of individual bubbles. The condition described by equation (11) is satisfied for bubbles in the Columbia River flows.
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Figure 4. The effect of different hydrodynamic processes on the evolution of a layer of bubbles illustrating (a) the evolution of concentration gradients, (b) hydrodynamic self-diffusion, and (c) growth of the the layer due to bubble growth. In Figure 4d, the rate of hydrodynamic diffusion exceeds the rate of bubble growth. Note the scale change of the x-axis in Figure 4c. In all calculations, $\mu = 1000 \text{ Pa s}$, and $n = 3$.

For the Columbia River flows, we assume a diffusivity of $\kappa = 10^{-10} \text{ m}^2/\text{s}$ [e.g., Zhang and Stolper, 1991], bubble radii of 2 mm [McMillan et al., 1989], a viscosity of $10^3 \text{ Pa s}$, and density of $3000 \text{ kg/m}^3$ and find that wavelengths $\lambda > 1 \text{ m}$ are unstable (which is similar to the observed spacing of layers; see Figure 1). Thus we propose that each wave or layer forms once a sufficient height of bubbles forms above the lower solidification front.

Equation (10) describes the conditions under which the increase of $\phi$ due to bubble growth exceeds hydrodynamic self-diffusion. The $\phi$ dependence of the rise speed $U$, described by equation (3), will affect only the vertical gradients of $\phi$ once an instability forms. Thus the problem for bubbles in lavas (with $a < O(1) \text{ cm}$ in basaltic lavas so that $\mathcal{R} \ll 1$) is different from the phenomenon shown in Figure 2. For $\mathcal{R} > O(1)$, such as the experiment with beer in Figure 2, bubbles rising through the clear fluid can penetrate far into the layer of bubbles, due to the inertia associated with the fluid displaced by the bubble, so that $\phi$ can increase in the layers. The limit in which inertia is important has been the focus of previous studies of concentration waves in suspensions and fluidized beds [e.g., Batchelor, 1988].

We have assumed in equation (3) that bubble growth is due to diffusion of gas from the magma into the bubbles. The growth of the instability simply requires a mechanism for increasing $\phi$, so that bubble growth due to pressure changes will also promote the formation of waves.

Finally, we note that the length scale described by equation (10) can be derived in a more insightful manner. The timescale for hydrodynamic self-diffusion to smooth concentration variations is $\tau_h = O(\lambda^2/\kappa_0)$, i.e., the layer thickness squared divided by the hydrodynamic diffusivity. The timescale for growth by diffusion is $\tau_g = O(a^2/\kappa)$. For growth of the instability, we require $\tau_h > \tau_g$, or $\lambda > (caU/\kappa)^{1/2}$, which is identical to equation (10).

Numerical Simulations

In order to illustrate the different processes more clearly, in Figure 4 we show the results of numerical simulations. We again consider a one-dimensional model and assume the suspension is monodisperse. Equation (6) is solved numerically using a Lax-Wendroff finite-difference method with upwind differences to minimize
transport errors [Press et al., 1989]. The initial distribution of bubbles has a Gaussian shape, and all model parameters are left in dimensional terms.

In Figures 4a and 4b, we illustrate the effects of two different physical processes: the effect of the concentration dependence of the rise speed and the effect of hydrodynamic self-diffusion, respectively. If the bubbles do not grow and there is no self-diffusion (Figure 4a), a sharp concentration gradient (and eventually a shock) forms at the trailing edge of the wave and the maximum concentration remains unchanged. The effect of self-diffusion, as illustrated in Figure 4b, is to smooth concentration gradients and thus to decrease the maximum amplitude of the concentration wave.

In Figures 4c and 4d, we show results which account for all the processes we expect to play a role. If the bubbles are allowed to grow, as illustrated in Figure 4c, then under certain conditions the amplitude of the wave can also increase. The particular values of parameters in Figure 4c correspond to typical bubble size, layer thickness, and diffusivities of the vesicle layers in the Columbia River flows. However, as shown in Figure 4d, for larger bubbles, the concentration of bubbles in the layer will decrease: \( \phi \) increases more slowly due to bubble growth by diffusion, whereas the rate of self-diffusion increases.

**Discussion**

The analysis presented here suggests that an instability, as illustrated schematically in Figure 5, may develop in lava flows containing bubbles resulting in the formation of horizontal layers of bubbles. Qualitatively, as suggested by McMillan et al. [1987], bubbles nucleate nearly continuously at lower solidification front and rise. Once a sufficiently thick layer of bubbles forms, with thickness described by equation (10), the instability can occur and the bubbles rise as discrete waves or layers. As the bubbles continue to grow, the thickness and spacing of layers may change due to the changing relative importance of bubble growth and hydrodynamic self-diffusion. The theoretically predicted spacing of bubble layers is \( \approx 1 \) m, which is similar to the spacing of layers in the Columbia River flows (see Figure 1).

Although there are few studies documenting the detailed bubble distribution in lava flows, periodic horizontal layers of bubbles within lava flows do not appear to be common features. However, there are also only a limited range of situations in which layers of bubbles will form and be preserved. The processes described above are expected to produce layers with typical thickness of 1 m so that we would expect only flows with thickness greater than several times the layer thickness will allow layers to develop and grow as the bubbles rise. In “thin” flows, with thickness than 10 m, vesicle layering is generally absent [e.g., Aubele et al., 1988], although some of the flows studied by Aubele et al. [1988] show weak layering. However, as expected, layers are found in thick flows in the Columbia River basalts (Figure 1), and subhorizontal bands of vesicles are also found in the Keweenawan plateau lavas [Green, 1989]. Vesicular layers are also found in drill cores in Kilauea Iki lava lake [e.g., Heits, 1987, Figure 7], although there are many other processes in addition to those discussed here which could both disrupt and promote the formation of layers in lava lakes.

We have assumed in this analysis that bubbles rise through a Newtonian fluid. A finite yield stress would prevent bubbles from rising until they grow to some critical size. Thus layers conceivably could develop from bubbles which nucleate at the lower solidification front, rise only when they become large enough, and allow a new generation of bubbles to form at the solidification front. However, at least in the Columbia River flows, the absence of bubbles in the lower portions of the flow suggests that the yield stress was sufficiently small that submillimeter size bubbles could rise freely.

**Flow Solidification**

Preservation of bubble layers in the solidified flow requires that the rate of solidification be sufficiently great that the layers do not catch up to each other and consolidate below the upper solidification front. Assuming the rate of solidification is governed by thermal diffusion through a crust with thickness \( L \) overlying the liquid lava,

\[
\frac{dL}{dt} = \mathcal{O} \left( \frac{D}{L} \right) \sim 10^{-7}\text{m/s}, \tag{12}
\]

where \( D \sim 10^{-6}\text{ m}^2/\text{s} \) is the thermal diffusivity and \( L \sim 30\text{ m} \). For a viscosity of \( 10^3\text{ Pa s} \), the rise speed of bubbles is \( \sim 10^{-3}\text{ m/s} \). As the bubbles approach the upper solidification front, the viscosity of the surround-
ing magma will increase as the temperature approaches the freezing point. If a viscosity 100 times greater is appropriate, then \( U_c \sim \frac{dL}{dt} \) and the layers of bubbles should be preserved. The actual rate of solidification may be about 1 order of magnitude greater due to convective circulation of water and steam along downward propagating cooling joints [Long and Wood, 1986] so that only a factor of 10 increase in viscosity is necessary to preserve layers of bubbles.

Secondary Instabilities

We have only considered the evolution of bubble concentration in the vertical direction. However, once a layer of bubbles forms, the layer is gravitationally unstable compared with the relatively bubble-free liquid above and below the layer. Thus a gravitational, or Rayleigh-Taylor, instability can occur, leading to the breakup or partial breakup of bubble-rich layers. This second type of instability can be seen in the experiment shown in Figure 2. As observed in Figure 2, the structure associated with the gravitational instability is less pronounced. Qualitatively, the rate of ascent of the small "bubble clouds" formed as a result of the instability is fast compared with that of individual bubbles and layers of bubbles, so that "bubble clouds" rise rapidly from the top of one layer to the bottom of the next layer. A similar instability in bubbly layers trapped beneath a high-viscosity fluid (e.g., the interface between a mafic and more silicic magma) has been studied experimentally by Thomas et al. [1993].

The formation of "cylinders" and "sheets" of vesicles is sometimes attributed to a Rayleigh-Taylor type instability [Goff, 1977], and vesicle cylinders appear to be common features [e.g., Goff, 1977; Aubele et al., 1988; Green, 1989]. Similar structures are found in active lava lakes: Vertical olivine-rich bodies found in several drill cores in Kilauea Iki lava lake are thought to form by rising streams of vesicles which entrain melt and olivine crystals and redistribute the crystals into vertical columns [e.g., Helts et al., 1989; Helts, 1980]. The formation and subsequent breakup of horizontal bubbly layers may form diapiric structures. However, vesicle cylinders appear to be associated with highly evolved melt, which suggests they develop at the solidification front [Goff, 1977].

It is worth noting that the instability of layers of bubbles is not identical to the classic Rayleigh-Taylor instability since a layer of bubbly fluid cannot be treated as a single-phase homogeneous fluid. As illustrated in Figure 6, within a layer of bubbles, the bubbles are rising upward, and the surrounding fluid must move down between the bubbles due to conservation of mass. Thus horizontal disturbances to layers will not necessarily be unstable.

Crystal Layering in Magmatic Systems

Layered structures in large intrusive igneous bodies are common features [e.g., Wager and Brown, 1968]. Early investigators favored models in which the layers are due to the gravitational sedimentation of crystals, whereas more recent models generally support the view that layering develops in situ [e.g., McBirney and Noyes, 1979].

The processes discussed in this paper may promote the formation of layers of crystals only for situations in which the layers consist of initially suspended crystals which settle through an otherwise quiescent liquid. This condition is not appropriate for most crystals in magma chambers, since convective velocities are thought to be much larger than sedimentation velocities [e.g., Martin and Nokes, 1989].

Waves in Bubbles in Magma Chamber and Conduits

The formation of concentration waves should occur in conduits and magma chambers if bubbles are present and magma velocities are small compared with bubble rise speeds so that convective motions in the liquid do not disrupt layers and disperse the bubbles. The model considered in the previous section, which neglects the effects of horizontal boundaries, will apply in conduits provided the conduit radius is much greater than the bubble radius. Variations of bubble concentration are thought to play a role in fire-fountaining at Kilauea [e.g., Wolfe et al., 1987; Head and Wilson, 1987] and the periodicity of eruptions at Stromboli [e.g., Blackburn et al., 1976]. In the former case, the rise speed of individual bubbles is probably too slow for instabilities
of the type described here to develop since magma ascent rates at depth in the rift zones are \( \sim 1 \text{ m/s} \) [e.g., Vergniolle and Jaupart, 1988]. By comparison, the rise speed of a bubble with radius 1 cm in a magma with viscosity 100 Pa s is about 1 cm/s. However, in magmatic systems which produce Strombolian eruptions, the magma ascent rate is \( \sim 0.1-1 \text{ cm/s} \) [e.g., Parfitt and Wilson, 1995] and thus is less than, or comparable to, the rise speed of bubbles.

The very large bubbles inferred to erupt in Stromboli [e.g., Blackburn et al., 1976; Ripepe et al., 1993; Vergniolle and Brandeis, 1994] may ultimately form from layers of bubbles, and the spacing of layers could govern the frequency of eruption. Assuming a viscosity of 100 Pa s and bubble radii of 2-5 mm, we estimate a wavelength of 3-30 m using equation (10). Coalescence within the layer will be promoted by the increased concentration of bubbles. For an ascent rate of 1 cm/s, bubble layer spacing of 3-30 m results in eruption intervals of 5-50 min, similar to the observed eruption intervals of 11-60 min [Chouet et al., 1974]. The gravitational instability discussed above will tend to be stabilised if the conduit diameter is smaller than the layer thickness.

Summary

Layers or waves of bubbles may form in suspensions of growing bubbles rising through a Newtonian fluid. The spacing of layers is determined by a balance between the growth of bubbles and hydrodynamic self-diffusion. Vesicular layers preserved in Columbia River flows may thus form by hydrodynamic processes and do not require the repeated injection of fresh volatile-rich magma or a periodic nucleation of bubbles [e.g., McMillan et al., 1989]. Layers may undergo a gravitational instability, producing diapirs or plumes of bubbles.

As we have noted throughout this discussion, a large number of approximations have been made in the analysis (this is, in general, true of any analysis of two-phase flows). However, the physical processes described in this paper, and illustrated in Figures 2 and 3, should hold regardless of the the actual details of the specific problem. Despite the simplifications, the results allow us to relate some of the physical properties of magmatic systems to certain magmatic processes; specifically, the model illustrates the sharpening of concentration gradients due to the concentration dependence of the rise speed and the smoothing of concentration gradients due to hydrodynamic self-diffusion.

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