BUBBLE GROWTH IN LUNAR BASALTS AND LUNAR VOLATILE BUDGET
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Introduction: Moon is usually said to be volatile-“free”. However, lunar basalts are often vesicular with mm-size bubbles (Fig. 1). The vesicular nature of the lunar basalts suggests that they contained some initial gas concentration. A recent publication estimated volatile concentrations in lunar basalts [1]. The volatile budget of Moon is important not only in terms of lunar evolution, but also in terms of lunar exploration. This report investigates bubble growth in lunar basalts and the controlling factors. We also discuss various means to constrain volatile contents in Moon.

![Vesicular lunar basalt displayed in the Smithsonian National Air and Space Museum.](image)

Fig. 1. Vesicular lunar basalt displayed in the Smithsonian National Air and Space Museum.

Diffusive Versus Convective Bubble Growth: Often it is easy to determine whether mass transport in bubble growth is controlled by diffusion or enhanced by convection. For example, bubble growth in rhyolitic melt during explosive volcanic eruptions [2] is usually controlled by diffusion due to the very high viscosity of rhyolitic melt (~1 MPa·s, [3]). On the other hand, bubble growth in beer [4] is convective due to low viscosity of beer (~1.9 mPa·s) and hence rapid rise of bubbles. For lunar basaltic melt, the viscosity is on the order of 1 Pa·s [5], and bubble growth may be either diffusive or convective. Hence, it is necessary to develop quantitative criteria to determine the conditions of convective versus diffusive bubble growth. The same criteria would also apply to bubble dissolution, crystal growth and dissolution, and droplet growth and dissolution.

Two conditions must be satisfied for convective bubble growth: (1) diffusion distance is longer than the expected convective boundary layer thickness, and (2) the diffusive boundary layer is shed due to the ascent of bubbles. Based on our analyses, growth or dissolution of a single bubble in an infinite fluid is convectively controlled under the following conditions:

$$\delta < (\pi D \eta)^{1/2} < U_t \quad \text{or} \quad t > \max(\delta^2/(\pi D), \pi D/\gamma^2),$$

where $\delta$ is the convective boundary layer thickness that can be estimated from fluid dynamics [6,7], $D$ is the diffusivity of the volatile component, $t$ is time, and $U$ is the ascent velocity of the bubble. For the growth of multiple interactive bubbles, no rigorous criteria have been developed but bubble growth in that case is more likely to be diffusive because bubble rise is more difficult with a bubble network.

Bubble Growth Modeling: Under conditions relevant to lunar basalts, bubble growth in a finite melt shell (i.e., growth of multiple regularly-spaced bubbles) is calculated following [2] and [8] for $t < \max(\delta^2/(\pi D), \pi D/\gamma^2)$. Initial H$_2$O content of 700 ppm [1] or lower is used and the effect of other volatiles (such as carbon dioxide, halogens, and sulfur) on bubble growth is ignored. H$_2$O solubility at low pressures [9], concentration-dependent diffusivity in a mid-ocean ridge basaltic melt [10], surface tension of 0.33 N/m [11], and lunar basalt viscosity [5] are used.

Results and Discussion: Because lunar atmospheric pressure is essentially zero, the confining pressure on bubbles is due to surface tension and the overlying magma. For example, surface tension pressure on a 1-mm-diameter bubble is 1.3 kPa, and a 1-m melt column contributes 4.7 kPa pressure. Due to low H$_2$O content in lunar basaltic melt (e.g., 700 ppm H$_2$O corresponds to a saturation pressure of 75 kPa), H$_2$O bubbles only grow in the upper layer of a basaltic melt column. Hence, vesicular lunar rocks come from very shallow depth.

Because volatile concentrations are low, bubble nucleation is expected to be extremely difficult. Furthermore, even ppm-level CO$_2$ concentration is expected to contribute majorly to bubble nucleation (likely more than the contribution of H$_2$O) due to its low solubility; for example, 700 ppm H$_2$O corresponds to a pressure of ~75 kPa, but 1 ppm CO$_2$ corresponds to a pressure of ~200 kPa) [9]. On the other hand, because bubble growth requires gas molecules to go in
the bubbles, once nucleated, bubble growth is expected to be largely controlled by H$_2$O.

Some modeling results are as follows. (1) Due to low confining pressure as well as low viscosity, even though volatile concentration is very low, once nucleated, bubble growth rate is extremely high (Fig. 2), much higher than typical bubble growth rates in terrestrial melts. Hence, mm-size bubbles in lunar basalts are not strange. (2) Because the pertinent pressures are so low, bubble pressure due to surface tension plays a major role in lunar bubble growth, contrary to terrestrial cases. (3) Time scale to reach equilibrium bubble size increases as the confining pressure increases. (4) Bubble growth rate and size are controlled largely by the initial H$_2$O content and the ambient pressure (Fig. 2). If one is independently constrained, the other may be roughly inferred from the vesicularity of lunar basalts. (5) Other important parameters in understanding bubble growth in lunar basalts include H$_2$O solubility in lunar basaltic melts (fairly well known), H$_2$O diffusivity in lunar basaltic melt (needs improvement), viscosity of lunar basaltic melt (needs improvement), and surface tension (fairly well known).

Constraining Pre-eruptive H$_2$O Concentration in Lunar Basalts: Although the work of Saal et al. [1] is a good start, the inferred H$_2$O concentration based on diffusion modeling is highly uncertain. One constraint of minimum gas pressure can be obtained from bubble size. Gas pressure must exceed the surface tension pressure of 2$\sigma$/r (in the case of zero ambient pressure). For example, for 1-mm-diameter bubbles, the gas pressure must be greater than 1.3 kPa. If this is due to H$_2$O (likely), it is equivalent to about 100 ppm H$_2$O. Other types of constraints on pre-eruptive gas content can come from investigations of melt inclusions in olivine phenocrysts as well as hydrous minerals such as apatite in lunar rocks. We plan to explore various ways to further constrain volatile concentrations in lunar basalts.

References: