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Theoretical study of nucleation and growth of water bubbles in ascending magmas: derivation of nucleation rate including viscosity and revisiting bubble number density

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It is important to quantify the unobservable behavior of magmas in the conduit during eruption, since the dynamics in the conduit controls the surface phenomena such as the shift between explosive and nonexplosive eruptions. In particular, the formation process of bubbles plays an important role as the driving force for eruptions together with the influence of the degassing process. There have been various kinds of studies to quantitatively understand the formation process of bubbles in magmas. One of them is the textural analysis of bubbles, which allows us to estimate the decompression rate of the ascending magma in the conduit from data of BND (Bubble Number Density) in pyroclasts, on the basis of the classical nucleation theory (CNT).

In the CNT the nucleation rate does not include the viscosity term, while the viscosity effect is usually taken into account in the growth process incorporating the Rayleigh-Plesset equation as the momentum equation. In the CNT, the nucleation rate is derived by considering the diffusional migration of the gas molecule in liquid phase to gas phase, neglecting the change of the molar volume. However, such a volume change induces the viscous flow in the melt surrounding an expanding bubble even in the nucleation stage. Therefore, we have to formulate the nucleation rate taking into account the viscosity effect of liquid.

Following Kagan's method for the bubble nucleation in a single component system, we have derived the nucleation rate for a two component system (silicate - water system), which explicitly includes the viscosity in the pre-exponential factor in terms of Péclet number. Péclet number is the ratio of two timescales: a timescale of the bubble growth by diffusion and a viscous relaxation time. In the previous research, the pre-exponential factor is independent of viscosity. On the other hand, in this study, the factor drastically decreases by orders of magnitude as the value of Péclet number decreases below unity under a given supersaturation.

Furthermore, we have numerically solved the time evolution of bubble nucleation and growth in magmas decompressed by a constant rate by using the newly derived nucleation rate. Like the results obtained in the previous version, two regimes have been found on the relationship among BND, diffusivity and viscosity: the diffusion-controlled regime where BND does not depend on viscosity but does only on diffusivity and the viscosity-controlled regime where BND exponentially increases with the increase of viscosity but is independent of diffusivity. Compared with the previous study, the transition point of two regimes moves to the higher-viscosity region and BND values are dramatically reduced by several orders of magnitude in the viscosity-controlled regime. Such a difference can be interpreted by the effect of viscosity on the pre-exponential factor. These results are expected to account for laboratory experimental results which are partly inconsistent with the previous theory.