An analytical study for 1-D steady flow in volcanic conduits: conditions for effusive eruptions due to vertical gas escape

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As magma ascends and decompresses, volatiles exsolve and volume fraction of gas increases. If gas remains trapped in the magma, the magma inflates and magma fragmentation occurs, and the flow changes from bubbly flow to gas-pyroclast flow. In contrast, if gas escapes from the magma efficiently, inflation of the magma is suppressed and the magma does not fragment up to the vent, leading to effusive eruptions which form lava domes or lava flows. Therefore gas escape from magma is a key process for effusive eruptions to occur. We analytically investigated the effects of vertical gas escape on eruption styles on the basis of a model for 1-dimensional steady flow in volcanic conduits. In our model, the vertical relative motion between gas and liquid is allowed and a new transitional region ('permeable flow region') is introduced between bubbly flow region and gas-pyroclast flow region. In this region, both the gas and the liquid are continuous phases, allowing the efficient vertical gas escape through the permeable flow structure.

In the 1-dimensional steady conduit flow model, the length of the region before magma fragmentation (Lb) and the length of the region after magma fragmentation (Lg) are analytically given as a function of magma discharge rate (q). The steady solution for a given total length of the conduit (Lt) is obtained by the relationship of Lb(q) + Lg(q) = Lt . The most important effect of the vertical gas escape is that the pressure at magma fragmentation decreases as the relative velocity in the permeable flow region increases. This induces a significant decrease of Lg(q), whereas Lb(q) is not largely affected. As a result, the steady solution which satisfies the relationships of Lg(q) = 0 and Lb(q) = Lt exists. This solution corresponds to effusive eruptions. This means that the gas escapes sufficiently and the pressure at fragmentation is smaller than the atmospheric pressure, and the flow reaches the vent without fragmentation.

We analytically determined the condition for the relationship of Lg(q) = 0 to be satisfied by using mechanical balance in the permeable flow region. The mechanical balance changes depending on magma discharge rate. When the magma discharge rate is larger than the critical value determined by liquid viscosity, conduit radius and initial volatile content, liquid-gas interaction force (Flg) is balanced with liquid-wall friction force (Flw). In this case, the condition for Lg(q) = 0 is governed by non-dimensional number 'A', which represents the ratio of the effects of Flw and Flg. On the other hand, when the magma discharge rate is smaller than the critical value, Flg is much greater than Flw. In this case, the condition for Lg(q) = 0 is governed by non-dimensional number 'B', which represents the ratio of the effects of the liquid weight and Flg. When the parameter A or B is larger than 1 and Lb(q) = Lt, effusive eruptions can occur. Our analytical method can successfully determine the condition for effusive eruptions without numerical calculations.