Effects of relative motion between gas and liquid on 1-D steady flow in volcanic conduits: origin of diversity of eruption styles

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The effects of vertical relative motion between gas and liquid on eruption styles are investigated on the basis of a model for 1-dimensional steady flow in volcanic conduits. As magma ascends and decompresses, volatiles exsolve and volume fraction of gas increases. As a result, magma fragmentation occurs and the flow changes from bubbly flow to gas-pyroclast flow. In our model, a transitional region ('permeable flow region') is introduced between the bubbly flow region and the gas-pyroclast flow region. In this region, both the gas and the liquid are continuous phases, allowing the efficient vertical escape of gas through the permeable structure.

The features of the conduit flow with the relative motion are described by non-dimensional numbers, A, B and E. The parameter A represents the ratio of effects of wall friction and gravitational load, and the parameter B represents the ratio of pressures at the vent and at the fragmentation level. Both A and B are proportional to magma flow rate. The parameter E is defined as the ratio of effects of liquid-wall friction force and liquid-gas interaction force in the permeable flow region, and represents the efficiency of gas escape from magma. The value of E is determined only by magma properties and geological conditions such as liquid viscosity, magma permeability and conduit radius. When the relative motion is taken into account, the pressure at the fragmentation level (P_f) decreases as the magma flow rate (A) decreases or the efficiency of gas escape (E) increases, because the effect of gas escape suppresses the increase in the gas volume fraction accompanied by magma ascent. When A is so small or E is so large that P_f is below the atmospheric pressure (P_a), the flow reaches the vent before fragmentation. On the other hand, when A is so large or E is so small that P_f is greater than P_a, the flow reaches the vent after fragmentation. The steady solutions of conduit flow in which the flow reaches the vent before and after fragmentation correspond to effusive and explosive eruptions, respectively. Because both A and B are proportional to the magma flow rate, the problem of the 1-dimensional steady conduit flow model is formulated as a problem to find a non-dimensional magma flow rate A as a function of the parameters related to magma properties and geological conditions (e.g., $B/A=G$ and E) under given boundary conditions. A graphical method to systematically find A is proposed.

The numbers and the types of the steady solutions of conduit flow (i.e., the assemblage of the steady solutions) largely depend on parameters related to magma properties and geological conditions. On the basis of the graphical method, the relationship between the assemblage of the steady solutions and the magma properties or the geological conditions is investigated. When the parameter E is larger than a critical value E_{cr}, only a single solution of effusive eruption exists. On the other hand, when E is smaller than E_{cr}, the assemblage of the solutions change depending on E, G and other geological conditions (e.g., conduit length). It is classified into the following five types: (1) Ef, (2) Ex, (3) Ef+Ex, (4) Ex+Ex, and (5) Ef+Ex+Ex, where Ef and Ex represent the solutions of effusive and explosive eruptions, respectively. The relationship between the assemblage of the solutions and the magma properties or the geological conditions can be expressed by a regime map in the parameter space of E, G and conduit length. The complex transition between effusive and explosive eruption styles observed in nature is explained by the fact that E is estimated to be smaller than E_{cr} in those eruptions.