Numerical simulation of magmatic differentiation -3

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Development of a numerical model to simulate thermal and chemical evolution of crustal magma chambers has been one of the main goals of petrology. In this study, two-dimensional model of magmatic differentiation, considering mass, momentum, and energy conservations, is presented. The model is applied to basaltic magma (Kutsugata lava) from Rishiri Volcano, and then the model calculations are compared with the observed compositional evolution of the Kutsugata magma.

A continuum model is used to treat momentum, energy, and species transport in solid-liquid phase change system (e.g., Bennon and Incropera, 1987), and the continuum equations were solved using SIMPLE algorism (Patankar, 1980). In order to examine the evolution of natural magmas, multicomponent thermodynamic approach was introduced. Solid fraction, melt composition, melt density, and latent heat of crystallization were calculated at a given temperature and magma composition, for individual grid cells at each time step and iteration step, which are linked to the calculations of x- and y-velocities, temperature, and chemical composition. For simplicity, crystallizing phase is limited to olivine and plagioclase in this study. Thermodynamic solution models for olivine of Hirschmann (1991), for plagioclase of Elkins and Grove (1990), and for silicate melt of Ghiorso and Sack (1995) were used.

The model was applied to the assumed magma chamber with a thickness of 500 m and width of 1000 m. The initial magma composition was that of the least differentiated samples in the Kutsugata lava (SiO2 51.4 wt.%). Initial magmatic temperature of 1117 C (liquidus) and pressure condition of 2000 bar (Kuritani, 1998) were used. The contact temperature was fixed to 600 C for simplicity. This corresponds to the emplacement of the magma in the crust with a temperature of 100-200 C.

Soon after the emplacement, the magma is cooled from the surroundings and crystallization occurs on the chamber walls. Melt phase is transported actively along the floor and sidewalls. This fluid motion is a compositional convection, which is caused by the density difference between the main magma and the interstitial melt within the mush zones along the chamber walls. For the composition of the Kutsugata magma, the density of interstitial melt tends to decrease as the temperature decreases. The low-density melt produced within the sidewall mush zones is transported upward and then moves laterally just below the roof mush zone. The fractionated melt extracted from the floor mush zone ascends in the main magma as plumes. Because of the transport of the fractionated melt, bulk composition of the mush zones becomes SiO2-poor and MgO-rich compositions. On the other hand, differentiation of the main magma proceeds by mixing of the low-temperature fractionated melt.

The main magma is zoned chemically from the SiO2-poor lower part to the SiO2-rich upper part. The main magma is likely to be evacuated from the magma chamber during eruption due to the lower viscosity than the high-crystallinity magma present along the chamber walls. Thus the chemical heterogeneity of the main magma is observed as whole-rock composition trends of the erupted magma. The calculated compositional variation of the main magma was, therefore, compared with the observed whole-rock composition of the Kutsugata lava. At a given SiO2 content, the calculated composition is low in MgO content compared with the observed content. This suggests that the extraction of the fractionated melt is restricted to the low-crystallinity region within the mush zone in the model calculations. In the actual magma chamber, the melt extraction might have occurred from the deeper mush zone by additional processes, such as settling of crystals within the mush zone (including compaction) which is not considered in this model.