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Mathematical and numerical modelling of fractional crystallization coupled with chemical exchanges and differential magma-solid transport in magma chambers

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The knowledge of the chemical evolution of magmas is a major concern in geochemistry and petrology. The jumps (or discontinuities) of chemical composition observed in volcanic series from the same province are also the subject of many studies. In particular the phenomenon of "Daly gap" (Daly 1910, 1925), the name given to the jump in chemical composition between the mafic rocks (basalt) and felsic rocks (trachyte, rhyolite, phonolite), corresponding to the absence or scarcity of rocks of intermediate composition (andesite), in both ocean and continental series. Some authors explain these compositional jumps thanks to the intervention of various geological phenomena which follow in time. For example, when a magma chamber turns from a closed to an open system, the lava of a specific composition is ejected to the surface, favoring the rise of the lightest, the most volatile-rich and the less sticky magmas to the surface of the earth (Geist et al., 1995, Thompson et al., 2001). The various explanations offered, although they agree satisfactorily with the natural data, most often lead us away from basic phenomena of melting / solidification, relative migration and chemical equilibrium between solid and liquid and involve various additional phenomena.

In our study, we propose a numerical modelling of the crystallization of a closed magma chamber. The physical and mathematical model distinguishes three main classes of processes occurring simultaneously:
- heat transfer and solidification,
- relative migration between the solid and the liquid magma,
- chemical reactions between the two (solid and liquid) phases.

Writing the partial differential equations with dimensionless numbers makes two parameters appear, they express the respective ratios of the solidification velocity on the transport velocity, and the kinetics of chemical exchange on the transport velocity. The speed of relative movement between the solid and the liquid, the solidification velocity and the chemical partition law between the solid and the liquid are assumed to be known; this last one may be non-linear and apply to major elements.

The model is written for one chemical component. It is splitted into two submodels, the crystallization/sedimentation model and the reactive transport model. The first is expressed by an hyperbolic partial differential equation and is solved by a three-point scheme, the second is solved using non-centered schemes. The computing program is written in Fortran 90, it is then validated by theoretical methods such as the method of characteristic curves, analytical calculations or by qualitative considerations. Numerical simulations show that, for some values of the dimensionless parameters and for some shapes of the chemical partition curves, the chemical composition of the magma chamber can be non homogeneous, particularly bimodal (two values of concentrations are preferred), starting from homogeneous initial conditions. The degree of this bimodality notably depends on the shape of the chemical partition law.

This model provides an intellectual framework to discuss the phenomena responsible for the variety of composition of magmatic rocks, particularly in the same province. It shows in particular that the coupling between three elementary phenomena, internal to the magma chamber, is enough to account for the bimodality or more generally the appearance of discontinuities in chemical compositions, without involving additional phenomenon.