Crystal growth in magmas and zoning profiles in crystals

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There are countless documents describing various types of chemical zoning in crystals of groundmass minerals to phenocrysts in igneous rocks including plutonic to volcanic rocks. However, the origins of such zoning patterns have been still controversial to lead the quite different interpretations of formation processes of rock textures. In this talk, after briefly reviewing theoretical works of crystal growth in terms of chemical zoning in crystals, I argue the significant influence of rate law of crystal growth on the zoning profile and discuss that the growth rate is controlled by the interplay with nucleation process through the mass conservation.
The relationship between crystal growth and zoning profile was studied theoretical first by Tiller et al (1953) in metallurgy, who derived the zoning profile under the steady state condition with constant growth rates. Smith et al (1995) derived the analytical solution for time-dependent problem with constant growth rates. Lasaga (1982) obtained the representative expressions for the solution to more general cases with time-dependent growth rate as function of composition at the interface, suggesting that the oscillatory zoning cannot be formed in a binary system such as plagioclase (anorthite and albite). On the basis of his numerical model, L'Heureux (1993) argued that the effective portioning coefficient between melt and crystal controls the occurrence of oscillatory zoning in a binary system. Recently, Gorokhova et al (2013) suggested that the multicomponent inter-diffusions play an important role in the development of oscillatory zoning as well as natural zoning pattern observed in eruption products. In these previous works, the coupling between the crystal growth and nucleation processes has not been taken into account. In the disequilibrium crystallization such as natural magmatic crystallization during volcanic eruptions, the nucleation process controls the supersaturation for crystal growth which, in turn, results in characteristic zoning profile through the mass conservation of crystallizing components and rate law of crystal growth. For instance, if we assume the constant nucleation rate, then the growth rate is found to be inversely proportional to time owing to the scaling arguments. Calculated zoning profiles well account for the observed zoning profile and core compositions as function of size for plagioclase microlites formed by the decompression-induced crystallization during explosive volcanic eruptions. Finally, I suggest that experimental reproductions of zoning profiles in systems effectively involving the nucleation process help our understanding for the natural crystallization processes especially in highly disequilibrium systems.

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