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Crystal sizes in intrusions of different dimensions: Constraints on the cooling regime and the crystallization kinetics

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Abstract—Crystallization in magmas depends on the crystallization kinetics as well as on the thermal regime. A dimensional analysis is presented which allows a simple understanding of the characteristics of crystallization. Characteristic scales for the rates of nucleation and crystal growth are used, denoted by I_m and Y_m respectively. The time–scale is given by $\tau_c = (Y_m^3 I_m)^{-1/4}$, and is close to the time required for crystallization to start in supercooled magma. The crystal size scales with $(Y_m/I_m)^{1/4}$, which provides a powerful constraint on the values of the nucleation and growth rates. The influence of the form of the kinetic functions for nucleation and growth is investigated. The form of the growth function relatively unimportant, in contrast to that of the nucleation function. In natural conditions following magma emplacement in cold country rocks, temperatures are continuously changing. Local scaling laws apply, whatever the boundary conditions are, with the characteristic time and crystal size given by $\tau = (Y^3 I)^{-1/4}$ and $R = (Y/I)^{1/4}$, where Y and I are the local rates. τ is the time to achieve crystallization and R the mean crystal size in a given piece of magma, and Y and I are the rates at which crystals were nucleated and grown locally. From petrological observations and laboratory crystallization experiments, the time–scale at high undercoolings is 2×10^5 sec. This gives the characteristic time for crystallization near the margins of intrusions. The time–scale is close to 10^8 sec in equilibrium conditions prevailing in the interior of large magma chambers. These can be compared to the characteristic times for cooling by conduction and convection. Several regimes are defined, depending on the intrusion dimensions. This allows a classification based on the average crystal size which agrees with petrological observations. The detailed study of dikes, sills and igneous complexes of different dimensions will allow constraints on poorly known conditions and parameters, such as the nucleation rate at small undercoolings.

INTRODUCTION

IN NATURE, magmatic crystallization proceeds in continuously evolving conditions, with both the melt temperature and composition changing. In large magma chambers, the end result is extremely complex, and the igneous record is difficult to decipher. Most studies so far have relied on equilibrium phase diagrams (MORSE, 1980) and on various dynamical processes such as thermal and compositional convection (HESS, 1960; JACKSON, 1961; WAGER and BROWN, 1968; MORSE, 1969; IRVINE, 1974; MCBIRNEY and NOYES, 1979; KERR and TAIT, 1986). The influence of the crystallization kinetics generally has been overlooked, despite a growing number of dynamic crystallization experiments in the laboratory (GIBB, 1974; WALKER *et al.*, 1976; DONALDSON, 1979; GROVE and BENCE, 1979; LOFGREN, 1980; KIRKPATRICK *et al.*, 1981; ing rate determines which phase nucleates first. The consequence is that the internal differentiation of magma bodies may not follow equilibrium paths, which presents an obvious problem when interpreting petrological observations. MORSE (1980, p. 229) and others (KIRKPATRICK, 1983; BAKER and GROVE, 1983) have recognized the petrological implications.

To estimate cooling rates in natural conditions, a common practice is to use simple thermal models such as those by JAEGER (1968) and then to evaluate the consequences for dynamic crystallization. What is seldom recognized is that the kinetics themselves influence the cooling rate because the thermal evolution is determined not only by the heat loss mechanism but also by the crystallization rate through the release of latent heat (KIRKPATRICK, 1976; BRANDEIS *et al.*, 1984). The evolution of crystallization in a magma body depends therefore