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An experimental investigation of texture evolution during continuous cooling

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Abstract

Textural evolution during a controlled cooling experiment has been quantified using bulk textural characterizations (mean crystal length, total numbers of crystals and modal olivine content) and crystal size distributions (CSDs). The experiments involved subliquidus melting of an olivine–glass mixture followed by cooling at a constant rate (92 °C h^{-1}) through the crystallization interval. Measured changes in population density, $n(L)$, for small (<0.3 mm) euhedral olivine crystals are shown to be consistent with a uniform crystal growth rate of 6.0×10^{-7} mm s^{-1}. The CSD trends for larger (>0.3 mm) skeletal crystals are broadly consistent with an exponentially increasing nucleation rate and with a uniform growth rate of 2.0×10^{-5} mm s^{-1}. However, the textural development of these crystals cannot be explained solely in terms of homogeneous nucleation and growth. Additional factors influencing the development of textures in the skeletal zone of the charges include grain impingement and development of skeletal overgrowths on the top of a layer of seed crystals.

CSD data is ideal for analyzing texture development because it is sensitive to the detailed structure of the crystal population and can be used to detect variations in behavior between different size classes. Here, population density trends for various crystal size classes are used as a tool for estimating the kinetics of crystal growth and nucleation in a cooling igneous system. This type of analysis can be used to gain insight into crystallization processes from CSDs without relying on assumptions regarding CSD shape. Examples of the use of population density trends in the evaluation of natural systems are provided for the case of crystallization in porphyritic olivine chondrules and in komatiite flows.
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Keywords: crystal size distributions; experimental petrology; kinetics; chondrules

1. Introduction

The texture of an igneous rock is a fundamental source of information about the physical conditions under which it crystallized. The numbers, sizes and shapes of the crystals comprising a sample reflect the nucleation and growth rates and the degree of departure from chemical equilibrium during its cooling history. These parameters are in turn dependent on the temperature and chemical composition of the melt and crystals. One of the primary goals in textural studies is to develop quantitative relationships between observable characteristics of the crystal population, the crystallization history of the magma and its thermal and chemical development. In this study, a series of crystallization experiments with controlled chemical and physical

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conditions were used to explore the detailed evolution of the texture of an olivine-rich system such as that in which porphyritic olivine chondrules were formed.

Early studies of crystallization used the simple geometry and cooling history of thin dikes and sills or lava lakes to relate the observed texture to magmatic cooling history. This type of work resulted in quantitative relationships between the cooling process and crystallization kinetics in natural systems (e.g., Lane, 1899, 1903; Winkler, 1949; Gray, 1970, 1978). In these studies, the texture was typically quantified using simple parameters such as the mean crystal length and the areal number density (number/cm^2). Since the introduction of crystal size distribution (CSD) analysis to petrological studies (Marsh, 1988, Cashman and Marsh, 1988), textural variations in igneous rocks have frequently been quantified in terms of changes in the CSD (e.g., Cashman, 1993) and a great deal of theory has been developed linking CSDs to kinetic processes (Marsh, 1998).

Experimental studies provide an invaluable perspective on texture development by linking measured textures to controlled thermal conditions. The progressive development of a particular texture can be directly observed (e.g., Kirkpatrick et al., 1976; Lofgren, 1983) or reconstructed from a series of quenched experiments (e.g., Jurewicz and Watson, 1985; Park and Hanson, 1999; Cabane et al., 2001; Ayers et al., 2003). Because of practical limitations in terms of sample size and experimental duration, experimental studies have more commonly been used to evaluate the detailed temperature dependency of crystal morphology and nucleation and growth rates (e.g., Lofgren, 1974a,b, 1980, 1983; Klein and Uhlmann, 1974; Donaldson, 1976; Kirkpatrick et al., 1976).

In the present study, we have used a series of quenched experiments to reconstruct the detailed development of a texture during cooling. In these experiments, the temperature was lowered at a constant rate to simulate natural cooling. The textures at different points along the cooling trajectory were quantified first using classical parameters such as mean grain size and number density, then using CSDs. As will be shown, the CSD method provides a more detailed description of the texture at each step during the crystallization process and can detect complexities in the crystallization process that are not apparent from simpler textural quantifications. Specifically, CSDs clearly indicate the different crystallization regimes in different parts of the experimental charge. Using the observed texture development, we demonstrate a new method for testing kinetic models and show how the results could be applied to crystallization in natural igneous systems.

2. Methodology

2.1. Experimental techniques

Dynamic crystallization experiments were carried out in a 1-atm, vertical-tube, gas-mixing furnace. The oxygen fugacity was fixed at approximately one log unit below the iron-wüstite buffer using a CO–CO_2 mixture. Temperature was monitored using a Type-B (Pt_6Rh_{94}:$Pt_{30}Rh_{70}$) thermocouple, which was calibrated to the melting point of pure Au (1064 °C) and is believed to be accurate to within 5 °C (Lofgren and Russell, 1986).

The starting material for each experiment consisted of 20% (by weight) San Carlos olivine crushed to pass through a 44-μm sieve and 80% crushed glass synthesized from reagent-grade oxide and carbonate powders. The olivine+glass mixture has a chemical composition similar to the PO material of Lofgren (1989), which is a synthetic analog of a porphyritic olivine chondrule, and has an estimated liquidus temperature of ~1550 °C. The chemical compositions of the glass, olivine and bulk starting material are given in Table 1. The texture of the starting material is shown in Fig. 1 and the textural parameters are shown in Table 2.

For each experiment, a pressed pellet containing 125 mg of the olivine+glass mixture was lightly sintered onto a 0.2-mm diameter $Pt_{90}Rh_{10}$ wire that had been twisted to form a ~4-mm diameter loop. The sample was suspended from a thermocouple rod and inserted into the hot spot of a furnace that was preheated to 1545 °C. The charge was then held at that temperature for 0.2 h to partially melt the glass–olivine mixture and to equilibrate with the flowing CO–CO_2 mixture. After this initial homogenization interval, the furnace

Table 1
Chemical composition of experimental materials

	Glass [a]	Olivine	SC [b]	PO [c]
SiO_2	49.8	40.5	47.9	46.9
TiO_2	0.05	0.01	0.04	0.04
Al_2O_3	7.20	0.05	5.77	5.67
Cr_2O_3	0.03	–	0.03	0.02
FeO	14.4	8.7	13.3	12.5
MnO	0.06	0.13	0.08	0.07
MgO	24.5	49.4	29.5	28.9
CaO	3.17	0.08	2.56	2.48
Na_2O	1.12	0.01	0.90	0.91
K_2O	0.13	–	0.11	0.11
Total	100.48	98.89	100.16	97.61

[a] Average of 31 point analyses.
[b] Bulk composition of 4:1 glass/olivine mixture. Calculation by mass balance.
[c] Synthetic analog of porphyritic olivine chondrule (Lofgren, 1989).