Crystal-size distributions of garnets in metapelites from the northeastern Bushveld contact aureole, South Africa

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ABSTRACT

Crystal size distributions (CSDs) provide information about the nucleation and growth conditions of crystals. In the present study, we investigated CSDs of garnets in metapelites in the Bushveld contact aureole to examine the mechanisms of garnet nucleation and growth and to deduce controlling factors of CSDs. The CSD shapes were evaluated in terms of the Law of Proportionate Effects crystal growth and of the thermally accelerated, diffusion-controlled nucleation and growth. We adopted both the non-parametric and parametric stereological methods to estimate three-dimensional crystal size distributions from two-dimensional measurements of crystal diameters. The studied garnets showed various CSD shapes: asymptotic, lognormal, and near-symmetric distributions. These varieties of CSDs are generally controlled by heating rate, metamorphic temperature, and duration of thermal effects due to the intrusion of the igneous body. The chemical composition of the host sedimentary rocks is an additional important factor in controlling CSD shapes: it affects garnet growth as a supply source of nutrients for the mineral. At the contact between the Rustenburg igneous rocks and the aureole, where a rapid increase of temperature and a migmatitic extraction of siliceous melts occurred, the CSD is asymptotic showing constant- or accelerating-nucleation rates. In contrast, at some distance from the igneous contact where a relatively slower rise of temperature occurred and lognormal to near symmetric CSDs were mainly generated, suggesting decaying-rate nucleation dominated. However, even in such thermal conditions, differences in chemical compositions of host rocks affected growth mechanisms of garnet porphyroblasts, which resulted in relatively symmetric and pseudo-lognormal CSDs of garnets in biotite- and quartz-rich layers, respectively, in a pelitic sample.

INTRODUCTION

Crystal size distributions (CSDs) of minerals provide clues to their growth mechanisms. Contrary to mineral-compositional data, which often give information on the latest event, textural information (especially CSDs) could provide indications of several events, including the original conditions of nucleation and growth and later modifications due to deformation or annealing. Several types of CSD shapes have been reported in geological papers, but the factors that control modes of CSD evolution in metamorphic rocks are still under investigation.

The population-balance model was first developed for analyzing CSDs in the chemical engineering industry (Randolph and Larson 1971) and then was applied to petrologic problems by Marsh (1988), Cashman and Marsh (1988), and Cashman and Ferry (1988). In this series of contributions, Cashman and Ferry (1988) demonstrated the applicability of the theory to metamorphic rocks. Their investigations were based on the assumptions that crystal growth rates are constant and that the rates are independent of the crystal sizes. Cashman and Ferry (1988) found a good linear relationship between crystal sizes of magnetites in contact metamorphic hornfelses and their population densities (in no/cm^4), and argued for constant nucleation and growth rates. They also described the departures from linearity for garnets in regionally metamorphosed pelites, especially in the region of small particle sizes, and ascribed them to later Ostwald ripening. However, Carlson (1999) showed that common CSDs in metamorphic rocks previously thought to have grown by Ostwald ripening could be reproduced by his thermally accelerated, diffusion-controlled (TADC) nucleation and growth mechanism without Ostwald ripening. Reasonable simulations also showed that Ostwald ripening is impossible in real rocks (Carlson 1999).

Eberl et al. (1998) provided a different method to investigate CSDs that was based on the Law of Proportionate Effects (LPE), in which growth rates depend on crystal sizes. Their theory was confirmed experimentally by Kile et al. (2000) using calcite nucleation and growth. Eberl et al. (1998) showed three basic theoretical shapes of CSDs: (1) asymptotic, (2) lognormal, and (3) the Lifshitz-Slyosov-Wagner (LSW) distributions. Eberl et al. (1998) also showed that CSDs of the metamorphic magnetite and garnet in Cashman and Ferry (1988) could be explained as asymptotic and lognormal distributions, respectively, with their theory without Ostwald ripening. Applying the LPE growth theory to real metamorphic rocks, the LSW distribution becomes problematic, because the LSW distribution is generated by Ostwald ripening. This point will be discussed briefly later in this paper.

In the present study, we investigated CSDs of garnets in pelitic hornfelses in the northeastern Bushveld contact aureole, South Africa, in terms of the LPE growth along with the TADC