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Nanoscale Structural and Chemical Analysis of Garnet-Quartz Grain Boundaries in Contact Metamorphic Rocks

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Grain boundaries in metamorphic rocks provide pathways for fluid transport and intergranular diffusion, and thus might control processes of mineral crystallization and equilibration. Remarkably little is known, however, about key properties of grain boundaries in natural metamorphic rocks. In this study, we characterize garnet–quartz grain boundaries in contact metamorphic samples at the nano-scale, using Transmission Electron Microscopy (TEM). We focus on the structural and chemical aspects of the phases adjacent to the grain boundary, including the presence of nano-pores, the crystallography of contrasting phases, and chemical compositions of the phases.

The Nelson Contact Aureole, British Columbia (Pattison & Tinkham, J Met Geol, 2009), exhibits increasing metamorphic grade over an $\sim$2 km section from chlorite grade distal from the intrusion to K-feldspar grade adjacent to the intrusion. Previous works have shown that the distribution of the garnet, staurolite, and andalusite isograds is inconsistent with predictions from thermal models, implying failure of some rocks to form expected equilibrium assemblages. The growth of porphyroblasts was seemingly limited by a failure of new phases to nucleate, itself resulting from the interplay of numerous atomic-scale process at the boundaries between grains. Here we focus on garnet, analyzing its boundaries with quartz in rocks that reached each of the garnet, staurolite, andalusite, sillimanite, and potassium feldspar isograds to discern whether progressive changes in grain boundary characteristics occur as a result of increasing metamorphic heating.

Suitable grain interfaces were initially identified optically. Then, micron-scale major element zoning maps of selected garnet crystals were made using electron dispersive spectrometry on an electron microprobe. This allowed us to determine approximate growth and/or breakdown histories of garnet crystals in each sample, including progressive growth in the garnet and staurolite zone samples and partial breakdown in the andalusite, sillimanite, and potassium feldspar zones. This ‘classic’ petrology was then integrated with nanoscale analysis of specific garnet–quartz grain boundaries, which were prepared for TEM using Focused Ion Beam (FIB) liftout and then analyzed on a JEOL 2100 TEM. TEM analysis included diffraction, imaging, and chemical characterization. Initial imaging reveals that grain boundaries are heterogeneously open on the nanoscale, with voids between neighboring phases as large as 400 nm. Subgrain boundaries are particularly prevalent in quartz crystals near the garnet–quartz interface, where a lack of dislocations is evidence for quartz recrystallization near peak temperature. Alternative methods of sample preparation are currently being explored to isolate the extent to which sample preparation may affect these interpretations.

Microprobe elemental maps suggest that garnet composition is relatively homogenous towards crystal rims, but maps collected by TEM reveal nm- to μm-scale compositional changes towards grain boundaries. This requires both elemental exchange from the grain boundary into the garnet porphyroblast, despite heterogeneities in interface porosity, and maintenance of very short-length-scale zoning at garnet rims. Such observations are likely to be important for understanding metamorphic processes at the atomic scale.