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Analytical electron microscopy of nanometer-scale hornblende lamellae: Low-temperature exsolution in cummingtonite

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ABSTRACT

Cummingtonite from central Massachusetts, which has experienced pervasive exsolution of hornblende, contains numerous hornblende precipitates (lamellae and discs) ranging in thickness from 2.5 μm to 4 nm that represent multiple generations of exsolution. The smallest precipitates were investigated using transmission electron microscopy and analytical electron microscopy to characterize the coherent cummingtonite-hornblende solvus at low temperature. In contrast to older (coarser) generations of exsolution lamellae, which are 0.5–2.5 μm in width, planar, and extend across entire grains, the youngest generation consists of nanometer-scale discs (4–80 nm thick and 10–1000 nm long) that represent exsolution at approximately 300 °C (Klein et al. 1996). Quantitative energy-dispersive X-ray analyses were obtained from discs as small as 20 nm in thickness, providing compositional data for coherent exsolution of hornblende at ~300 °C. Surprisingly, these tiny discs have a lower Ca content and a higher Al content than the coarser, higher temperature lamellae. These compositions appear to lie well within miscibility gaps of the equilibrium and coherent solvi for cummingtonite-hornblende (in terms of Ca $\leftrightarrow$ Fe^{2+} exchange) at low temperatures, and may represent a more tschermakitic hornblende coexisting with cummingtonite with excess Al relative to Ca. The composition of the cummingtonite host between nanometer-scale discs is very low in both Ca and Al relative to bulk cummingtonite analyses that were obtained from electron microprobe analyses of 1–2 μm areas.

Compositional profiles across host areas were measured to help interpret the unexpected chemistries of the nanometer-scale discs. A profile across the precipitate-free zone between a coarse hornblende lamella and a group of nanometer-scale hornblende discs shows downward concavity for Ca and Al, as expected for incomplete diffusion between the precipitation zone and the pre-existing hornblende lamellae. A profile measured between two nanometer-scale discs shows downward concavity for Al and nearly constant to slight upward concavity for the Ca content, suggesting incomplete Al diffusion before completion of the exsolution process, but a near-equilibrium state for Ca. However, the Ca profile could also represent incomplete diffusion, if the hornblende discs had started coarsening at the expense of other (shrinking) discs by means of the Gibbs-Thomson (capillary) effect. The observed profiles suggest that, relative to Al, Ca was the faster diffusing element when the exsolution and coarsening processes stopped.