

Thermodynamics of the amphiboles: Anthophyllite-ferroanthophyllite and the ortho-clino phase loop

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ABSTRACT

Ten new single-crystal X-ray structure refinements of unheated and heat-treated anthophyllite, new measurements of the optical indicatrix of anthophyllite, and previously published data from Mössbauer spectroscopy of heated anthophyllite, show that temperature-dependent long-range order of Fe²⁺ and Mg on the M-sites of cummingtonite-grunerite and anthophyllite may be considered identical for the purpose of thermodynamic modeling. The difference in solution properties between the monoclinic and orthorhombic series, as expressed in the composition (X_{Fe}) dependence of $\ln K_D$ in natural amphibole pairs, is accommodated through adjustment of an enthalpic term that is independent of order-disorder.

End-member thermodynamic properties of cummingtonite and ferroanthophyllite are derived from those already known for anthophyllite and grunerite respectively, using intercrystalline K_D data and a fit of the T - X_{Fe} phase loop to two critical field constraints: middle amphibolite-facies amphibolites and upper amphibolite-facies metaperidotites. Amphibolites suggest a transition temperature in the system FMSH at ≈ 555 °C and $X_{\text{Fe}} \leq 0.3$, whereas metaperidotites suggest a transition temperature of ≈ 650 °C at $X_{\text{Fe}} \leq 0.1$. $\ln K_D$ for Fe-Mg exchange between cummingtonite and anthophyllite passes through zero at $X_{\text{Fe}} \approx 0.7$, and as a result the T - X_{Fe} phase loop shows a minimum at this composition.

Extrapolated end-member transition temperatures are estimated to be ≈ 800 °C (Mg) and ≈ 450 °C (Fe). At its breakdown to enstatite + quartz + H₂O (790 °C at 5 kbar), anthophyllite is marginally stable with respect to end-member cummingtonite, and the addition of Ca renders the breakdown reaction metastable. A stability field is possible for end-member ferroanthophyllite. Cummingtonite-anthophyllite phase relations mirror those of the analogous clino- and orthopyroxene.