The incorporation of chlorine into calcium amphibole

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ABSTRACT

The exchange of halogens between fluids and solid silicates holds considerable potential to shed light on fluid-rock interactions associated with various geological processes, including seawater-ocean-crust interaction, crustal and mantle metasomatism, and economic deposit formation. This study reports on how variations in formation conditions (temperature, pressure, hydrogen fugacity), bulk composition (Na and K ratio), and choice of starting material salts affect the Cl contents of calcium amphiboles synthesized specifically from ferro-pargasite and hastingsite bulk compositions. Syntheses were attempted over the range of 600–950 °C and 0.1–0.45 GPa at log fO2 of 1.4 to 2.4 (equivalent to −0.9 to −2.1 log fO2 below the fayalite-magnetite-β-quartz oxygen buffer, or ΔFMβQ) for durations of 111–672 h. Amphiboles were characterized by powder X-ray diffraction and electron microprobe, with cation proportions calculated on the basis of an assumed 18% ferric iron content. Amphiboles formed from the ferro-chloro-pargasite bulk composition [NaCa(Fe4+Al)(Al2Si6O22)Cl2] had Cl contents of only about 0.5 atoms per formula unit (apfu), compared to the intended 2.0, and whose stabilities were about 70 °C lower at 0.1–0.2 GPa than reported in a previous study of Cl-free (OH-bearing) ferro-pargasite. Syntheses on the ferro-pargasite bulk composition in the presence of a brine with a nominal mole fraction of Cl (XCl) of 0.3 over the range of 700–950 °C at 0.2 GPa showed that temperature had less effect on the Cl content of the amphibole than small variations in the Cl content assessed after treatment. For the chloro-hastingsite bulk composition [NaCa(Fe3+Fe3+)Al2Si6O22Cl2], the Cl content of the product amphibole was unaffected by the specific choice of chloride salt or salt combinations (NaCl, CaCl2, FeCl2), but showed a direct correlation with the substitution of K for Na. Experiments done over the range of 0.10–0.45 GPa at 700 °C and at −1.3 log fO2, ΔFMβQ showed an increased rate of nucleation of amphibole with increasing pressure for a hastingsite bulk composition with 40% substitution of K for Na, but no variation in the Cl content of the amphibole. Classification of the amphiboles formed in this study showed that several were well outside their intended field, with some of those formed from the ferro-pargasite bulk composition straddling the boundary between hastingsite and ferro-pargasite, while several formed from the hastingsite bulk composition were actually ferro-ferri-hornblendes. These results confirm that K more so than Na is important for the incorporation of Cl into calcium amphiboles, and that Cl-bearing ferro-ferri-hornblende, with low A-site Na + K, can form even from mixtures with abundant Na + K. Combining these observations with the strong correlation between Cl content and Fe# (=[Fe3+/(Fe3++Mg)]) noted in previous studies, a general correlation was found to exist between the Cl content and the FeAIK index, defined as Fe# (1/3Al + K), which combines the effects of Fe#, tetrahedrally coordinated Al (1/3Al), and K content. A linear trend is observed once a minimum value of about 0.34 in the FeAIK index is reached. The implication is that the crystal-chemical controls for Cl incorporation in calcium amphiboles are dominated by substitution of Fe3+ for Mg, 1/3Al for Si, and K for Na into the crystallographic A site with a linear dependence at the rate of 0.45 Cl per FeAIK index above a minimum value of about 0.34.

Keywords: Ferro-pargasite, hastingsite, chlorine, chloro-amphibole, synthesis, ferro-ferri-hornblende

INTRODUCTION

In contrast to a relatively rich history of experimental studies on F-bearing amphibole synthesis and stability (e.g., Bowen and Schairer 1935; Comeforo and Kohn 1954; Gilbert et al. 1982; Robert et al. 1989; Raudsepp et al. 1991; Jenkins and Hawthorne 1995; Pavlovich and Jenkins 2003), there are few experimen-

tal studies on the incorporation of Cl into amphiboles. With a growing interest in the use of halogens to monitor geological processes ranging from seawater-ocean-crust interactions (e.g., Barnes and Cisneros 2012; Kendrick et al. 2015) and crustal shear-zone metasomatism (Kusebauch et al. 2015) to mantle metasomatism (Frezzotti et al. 2011; Selverstone and Sharp 2011) and the formation of economic deposits (Yardley and Bodnar 2014), there is a need to understand the compositional variations that permit uptake of Cl by amphibole. To be sure,