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Cl incorporation into successively zoned amphiboles from the Ramnes cauldron, Norway

HISAO SATO,* YOSHIAKI YAMAGUCHI, AND KUNIAKI MAKINO

Department of Geology, Faculty of Science, Shinshu University, Asahi, Matsumoto 390, Japan

ABSTRACT

Amphibole from alkali granites in the Ramnes cauldron in the Oslo rift was altered hydrothermally by corrosion and growth through multiple events of fluid circulation. The alteration developed successive zones of amphibole at the crystal margins, resulting in a (1) brownish ferro-edenitic hornblende core (FE), (2) deep bluish-green hastingsitic hornblende zone (HH), and (3) light-greenish Fe-rich actinolite rim (FA). The edenitic core preserves the original igneous amphibole composition. The Cl content of amphibole strongly increases from the FE (0.78–0.82 wt%) to the HH zone (2.07–2.96 wt%) and abruptly decreases in the FA rim (0.01–0.36 wt%). In the Cl-rich HH amphibole zone, amphibole has characteristically high Cl content [2.96 wt%, 0.82 atoms per formula unit (apfu)] and high concentrations in both $^{[4]}Al$ (1.73 apfu) and A-site occupancy (0.86 apfu) with a large K/(Na + K) value of 0.47.

Both $^{[4]}Al$ and A-site occupancy increase systematically with positive correlation with Cl content throughout the three amphibole zones. On the other hand, Fe^{2+} content is not so simply correlated to the Cl content. Based on crystal structure considerations on Cl-rich amphiboles, the cation substitutions are illustrated by structural (geometrical) constraints for $^{[4]}Al$ and by a chemical constraint for Fe^{2+}. These contributions for Cl incorporation are expressed empirically by $\ln(Cl/OH)_{amp} = \ln(Cl/OH)_{fluid} + A \cdot {}^{[4]}Al \cdot Fe^{2+}/RT + B/RT$, where A and B are constant. $^{[4]}Al \cdot Fe^{2+}$ vs. ln(Cl/OH) plots of the three distinct amphibole zones suggest different fluid conditions in chemistry and temperature for the three zones. The zoning was developed through two stages of hydrothermal alteration. In the early hydrothermal event, a saline and high-temperature fluid altered the original hornblende (FE) to the Cl-rich HH zone. Late stage alteration by a high Fe/Cl and relatively low-temperature fluid partially over-printed the FA zone at the crystal margin.