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Phosphate-halogen metasomatism of lunar granulite 79215: Impact-induced fractionation of volatiles and incompatible elements†

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Abstract

In the last decade, it has been recognized that the Moon contains significant proportions of volatile elements (H, F, Cl), and that they are transported through the lunar crust and across its surface. Here, we document a significant segment of that volatile cycle in lunar granulite breccia 79215: impact-induced remobilization of volatiles, and vapor-phase transport with extreme elemental fractionation. 79215 contains ~1% volume of fluorapatite, $Ca_5(PO_4)_3(F,Cl,OH)$, in crystals to 1 mm long, which is reflected in its analyzed abundances of F, Cl, and P. The apatite has a molar F/Cl ratio of ~10, and contains only 25 ppm OH and low abundances of the rare earth elements (REE). The chlorine in the apatite is isotopically heavy, at $\delta^{37}Cl = +32.7 \pm 1.6‰$. Hydrogen in the apatite is heavy at $\delta D = +1060 \pm 180‰$; much of that D came from spallogenic nuclear reactions, and the original δD was lower, between +350‰ and +700‰. Unlike other P-rich lunar rocks (e.g., 65015), 79215 lacks abundant K and REE, and other igneous incompatible elements characteristic of the lunar KREEP component. Here, we show that the P and halogens in 79215 were added to an otherwise "normal" granulite by vapor-phase metasomatism, similar to rock alteration by fumarolic exhalations as observed on Earth. The ultimate source of the P and halogens was most likely KREEP, it being the richest reservoir of P on the Moon, and 79215 having H and Cl isotopic compositions consistent with KREEP. A KREEP-rich rock was heated and devolatilized by an impact event. This vapor was fractionated by interaction with solid phases, including merrillite (a volatile-free phosphate mineral), a Fe-Ti oxide, and a Zr-bearing phase. These solids removed REE, Th, Zr, Hf, etc., from the vapor, and allowed the vapor to transport primarily P, F, and Cl, with lesser proportions of Ba and U into 79215. Vapor-deposited crystals of apatite (to 30 μm) are known in some lunar regolith samples, but lunar vapor has not (before this) been implicated in significant mass transfer. It seems unlikely, however, that phosphate-halogen metasomatism is related to the high-Th/Sm abundance ratios of this and other lunar magnesian granulites. The metasomatism of 79215 emphasizes the importance of impact heating in the lunar volatile cycle, both in mobilizing volatile components into vapor and in generating strong elemental fractionations.

Keywords: Lunar, apatite, volatiles, metasomatism, Apollo 79215