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

ALLAN H. TREIMAN1,*, JEREMY W. BOYCE2, JULIANE GROSS3, YUNBIN GUAN2, JOHN M. EILER2 AND EDWARD M. STOLPER2

1Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, Texas 77058-1113, U.S.A.
2Division of Geological and Planetary Sciences, California Institute of Technology, 1200 E. California Boulevard, Pasadena, California 91125, U.S.A.
3Department of Earth and Planetary Sciences, American Museum of Natural History, Central Park West at 79th Street, New York, New York 10024, U.S.A.

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 δ^31Cl = +32.7 ± 1.6‰. Hydrogen in the apatite is heavy at δD = +1060 ± 180‰; most 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 magnesium 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

INTRODUCTION

The recent finds of relatively abundant water in lunar materials and on its surface have spiked interest in the origins and histories of lunar volatiles (Feldman et al. 2001; Saal et al. 2008, 2013; Pieters et al. 2009; Boyce et al. 2010; McCubbin et al. 2010a, 2010b; Greenwood et al. 2011; Hauri et al. 2011; Liu et al. 2012). However, the overall abundance of volatile species in the Moon is controversial (e.g., Sharp et al. 2010; Paniello et al. 2012). The mineral apatite, Ca_5(PO_4)_3(OH,F,Cl), is widespread among lunar samples (Meyer 2012), and has been central to studies of lunar volatiles as an indicator of their absolute and relative abundances, and the isotopic compositions of H and Cl (Boyce et al. 2010, 2013; McCubbin et al. 2010a, 2010b, 2011; Sharp et al. 2010; Greenwood et al. 2011, 2012; Tartese and Anand 2013; Tartese et al. 2013; Robinson et al. 2013; Barnes et al. 2013, 2014).

Recent studies have emphasized the abundances and origins of lunar volatile species (and their unusual isotopic characteristics), but the recognition that volatile constituents are widespread on the Moon suggests the possibility that volatile-mediated mass transfers and chemical fractionations could also be widespread. The best-known lunar example of volatile-mediated mass transfers, “rusty rock” 66095, is unique (Hunter and Taylor 1981; Shearer et al. 2012a; Burger et al. 2013; Provencio et al. 2013), and S-rich vapors have been implicated in sulfidation of some

* E-mail: Treiman@lpi.usra.edu
† Special collection papers can be found on GSW at http://ammin.geoscienceworld.org/site/misc/specialissuemlist.xhtml.