

## The Zn, S, and Cl isotope compositions of mare basalts: Implications for the effects of eruption style and pressure on volatile element stable isotope fractionation on the Moon

ANTHONY GARGANO<sup>1,2,\*†</sup>, JAMES DOTTIN<sup>3</sup>, SEAN S. HOPKINS<sup>4</sup>, ZACHARY SHARP<sup>1,2</sup>,  
CHARLES SHEARER<sup>5</sup>, ALEX N. HALLIDAY<sup>4,6</sup>, FIONA LARNER<sup>4</sup>, JAMES FARQUAR<sup>3,7</sup>, AND JUSTIN I. SIMON<sup>8</sup>

<sup>1</sup>Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131-0001, U.S.A.

<sup>2</sup>Center for Stable Isotopes, University of New Mexico, Albuquerque, New Mexico 87131-0001, U.S.A.

<sup>3</sup>Department of Geology, University of Maryland, College Park, Maryland, 20742, U.S.A.

<sup>4</sup>Department of Earth Sciences, University of Oxford, OX1 3AN, U.K.

<sup>5</sup>Institute of Meteoritics, University of New Mexico, Albuquerque, New Mexico 87131-0001, U.S.A.

<sup>6</sup>The Earth Institute, Columbia Climate School, Columbia University, New York, New York 10025, U.S.A.

<sup>7</sup>Earth System Science Interdisciplinary Center, College Park, Maryland 20742, U.S.A.

<sup>8</sup>Center for Isotope Cosmochemistry and Geochronology, Astromaterials Research and Exploration Science Division, The Lyndon B. Johnson Space Center, National Aeronautics and Space Administration, Houston, Texas 77058, U.S.A.

### ABSTRACT

We compare the stable isotope compositions of Zn, S, and Cl for Apollo mare basalts to better constrain the sources and timescales of lunar volatile loss. Mare basalts have broadly elevated yet limited ranges in  $\delta^{66}\text{Zn}$ ,  $\delta^{34}\text{S}$ , and  $\delta^{37}\text{Cl}_{\text{SBC+WSC}}$  values of  $1.27 \pm 0.71$ ,  $0.55 \pm 0.18$ , and  $4.1 \pm 4.0\%$ , respectively, compared to the silicate Earth at 0.15,  $-1.28$ , and 0‰, respectively. We find that the Zn, S, and Cl isotope compositions are similar between the low- and high-Ti mare basalts, providing evidence of a geochemical signature in the mare basalt source region that is inherited from lunar formation and magma ocean crystallization. The uniformity of these compositions implies mixing following mantle overturn, as well as minimal changes associated with subsequent mare magmatism. Degassing of mare magmas and lavas did not contribute to the large variations in Zn, S, and Cl isotope compositions found in some lunar materials (i.e., 15‰ in  $\delta^{66}\text{Zn}$ , 60‰ in  $\delta^{34}\text{S}$ , and 30‰ in  $\delta^{37}\text{Cl}$ ). This reflects magma sources that experienced minimal volatile loss due to high confining pressures that generally exceeded their equilibrium saturation pressures. Alternatively, these data indicate effective isotopic fractionation factors were near unity.

Our observations of S isotope compositions in mare basalts contrast to those for picritic glasses (Saal and Hauri 2021), which vary widely in S isotope compositions from  $-14.0$  to  $1.3\%$ , explained by extensive degassing of picritic magmas under high- $P/P_{\text{sat}}$  values ( $>0.9$ ) during pyroclastic eruptions. The difference in the isotope compositions of picritic glass beads and mare basalts may result from differences in effusive (mare) and explosive (picritic) eruption styles, wherein the high-gas contents necessary for magma fragmentation would result in large effective isotopic fractionation factors during degassing of picritic magmas. Additionally, in highly vesiculated basalts, the  $\delta^{34}\text{S}$  and  $\delta^{37}\text{Cl}$  values of apatite grains are higher and more variable than the corresponding bulk-rock values. The large isotopic range in the vesiculated samples is explained by late-stage low-pressure “vacuum” degassing ( $P/P_{\text{sat}} \sim 0$ ) of mare lavas wherein vesicle formation and apatite crystallization took place post-eruption. Bulk-rock mare basalts were seemingly unaffected by vacuum degassing. Degassing of mare lavas only became important in the final stages of crystallization recorded in apatite—potentially facilitated by cracks/fractures in the crystallizing flow. We conclude that samples with wide-ranging volatile element isotope compositions are likely explained by localized processes, which do not represent the bulk Moon.

**Keywords:** Zinc isotopes, sulfur isotopes, chlorine isotopes, lunar volatiles, degassing; Experimental Halogens in Honor of Jim Webster