

Discovering lost lunar magmas using Apollo zircons. M. Barboni¹, D. Trail², and K. D. McKeegan³

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Introduction: Unlike Earth, the Moon retains a relatively intact memory of the first 500 Ma of its history, and investigations of the chemical and isotopic compositions of these samples returned during Apollo missions has vastly improved our understanding of planetary formation and differentiation. That said, deciphering the lunar magmatic history is challenging because most lunar samples are impact-derived breccia or regolith that contain an amalgam of rocks and minerals that can have various origins. Additionally, the largest intact fragments of igneous rock rarely exceed 1 cm in size. Even so, these mineral-bearing fragments often show evidence of recrystallization or chemical modification linked to impacts. This makes connections between melt composition – whether endogenously or exogenously produced – and lunar magmatic history fraught with challenges. Some minerals, such as zircon, are extremely resistant to chemical exchange during heating; moreover, this mineral is a common target for geochronological studies because it can structurally accommodate U but excludes Pb. These characteristics make it an ideal mineral to see past the complex thermal histories. Zircon (ZrSiO_4) also incorporates impurities, such as Ti and Hf, that provide insights into its host melt source and evolution. However, what has been missing is a robust tool that would allow the major elements chemical composition of the different types of magmas present on the Moon, both primary (direct products of the Lunar Magma Ocean differentiation) and secondary (magmas generated by subsequent impacts), to be determined through analysis of zircon chemistry.

Method: We propose a new approach to decipher lunar magma major element compositions by using chemical and temporal information preserved within Apollo zircons. Even though most lunar zircon are inferred to be derived from ur-KREEP [1], the mere presence of zircon is not specifically diagnostic of a rock type or melt composition. We discovered that Al substitutes into the zircon lattice [2], and more recently, that this major rock-forming element serves as a proxy for the composition of the melt the zircon crystallized from (specifically the Aluminum Saturation Index, $ASI = \text{molar ratio of } \text{Al}_2\text{O}_3/[\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}]$) [3]. Laboratory experiments define uptake of Al in zircon as a function of melt composition [4], therefore providing a potential way to quantify melt composition of lunar zircons orphaned from their source rocks.

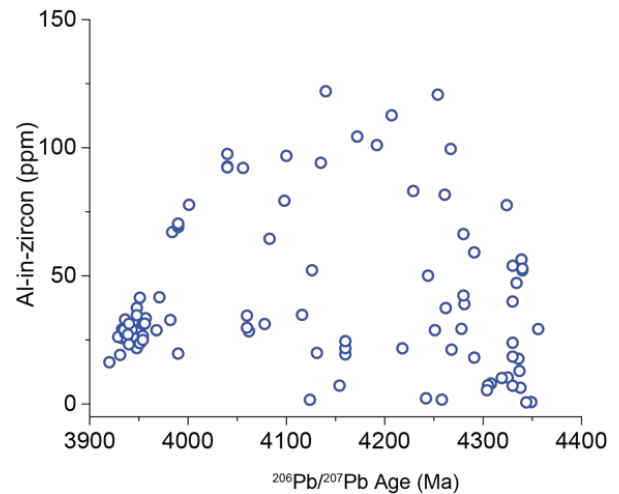


Figure 1: Al-in-zircon concentration versus crystallization age for 100 Apollo zircons. The U-Pb geochronology and Al concentration data were collected with the UCLA ims1290 ion microprobe.

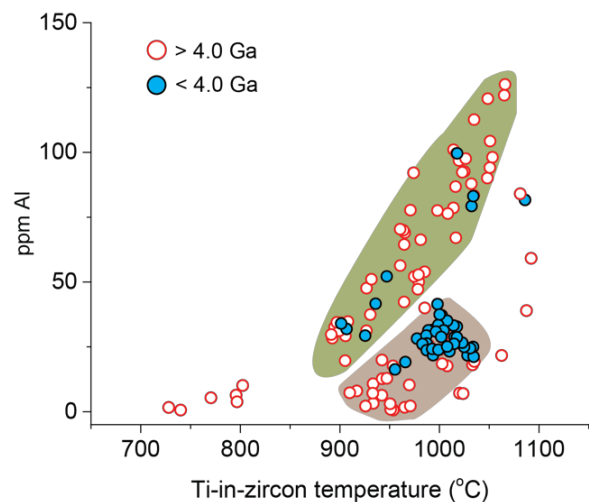


Figure 2: Al-in-zircon contents (in ppm) versus apparent crystallization temperatures plotted for about 100 Apollo zircons, binned by ages (< 4.0 Ga includes ages ranging from 3.95 Ga to 4.00 Ga; > 4.0 Ga includes ages ranging from 4.01 Ga to 4.35 Ga). Ages are Pb-Pb dates obtained on the same zircon areas that were measured for Al content. Two distinct melt compositions stand out, color-coded in red and green.

Results: Preliminary Al-in-zircon lunar data, collected on grains ranging from 3.95 to 4.35 Ga, reveal major Al content variations in lunar zircons, ranging from 1 to over 100 ppm (Figure 1). This strongly suggests that lunar zircons crystallized from magmas having diverse compositions. When correlated with Ti-in-zircon crystallization temperatures calculated by assuming equal silica and titania activities [5], two different groups of composition can be identified (high Al-content and low Al-content, see Figure 2). Our present experimental work, specifically designed to explore the meaning of Al in terrestrial zircon, demonstrates that that Al concentration in zircon is at least a function of melt composition and temperature[4]. If these conclusions are qualitatively valid for lunar zircons, results presented in Figure 2 imply at least two distinct melt compositions. With experiments specifically designed to address zircon-melt Al partitioning lunar-analog melts, there is significant potential to reveal melt ASI (Aluminum Saturation Index). Interestingly, the Al-content also seems to be correlated to the zircon crystallization ages, with the younger grains (< 4 billion years) displaying lower ASI values (Figure 2).

Discussion: Our preliminary data show the potential of using lunar zircons to track the major elements compositions of the magmas they crystallized from. The Al content in zircon, while coupled to Ti-temperatures and crystallization ages provide unique insights into the magmatic evolution of the Moon. Our preliminary data strongly suggest that Apollo zircons crystallized from at least two distinct melt compositions. Further work is needed to identify the most likely sources of those two types of melt, starting with identifying the potential composition of possible end-members, to which we can then compare our data. Such end-members should include products of the LMO differentiation (for example KREEP compositions from which primary zircons might have crystallized), as well as impact melts that could have crystallized secondary zircon grains. Once experiments specifically designed for lunar conditions have been completed and the ASI of the lunar melts derived from the Al content of the lunar zircons, those will be compared to the ASI inferred from potential end-members.

References: [1] Taylor D. et al. (2009) *EPSL* 279, 157-164. [2] Trail D. et al. (2011) *Am. Mineral.*, 96, 60–67. [3] Trail D. et al. (2017) *G-cubed*, 18, 1580-1593. [4] Wang Y., and Trail, D (2019) *Chem. Geol.* (in revision). [5] Ferry J. M. and Watson E. B. (2007) *CMP* 154, 429–437;