

Investigating the H₂O content and H isotopic composition of the primitive lunar magma ocean (LMO) cumulates

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Abstract

The lunar interior is now believed to be much wetter than was envisaged during the Apollo era [e.g. 1]. We have investigated the OH content and H isotopic composition of apatite grains in two lunar magnesian (Mg) suite rocks and demonstrate that the primitive lunar magma ocean (LMO) cumulates contained up to 6 ppm H₂O. We also show that the primitive cumulates were characterized by a δD signature similar to the bulk Earth, and propose that the H isotopic composition of the LMO was most likely retained from the proto-Earth during the Moon-forming event.

1. Introduction

Recent re-analyses of lunar samples for their volatile inventories have largely focused on the products of basaltic volcanism, i.e. picritic glasses and apatite in mare basalts [1-7]. In the context of the LMO model these products are thought to be derived from the partial melting of 'mixed' LMO mafic cumulates following the purported cumulate overturn event at ~ 3.9 Ga [e.g. 8]. The OH contents of mare basalts extend up to 12000 ppm and δD values range from 400 to 1100 ‰ [1-7]. In contrast very little work has been published on the volatile contents of rocks comprising the lunar crust but the few studies of apatite show that OH contents extend up to 1000 ppm (nominally anhydrous minerals contain up to 20 ppm OH) [4-6, 9-11], with δD values between ~ 200 and 700 ‰ [6,9,11]. The significance of analysing crustal rocks is that they may hold the key to understanding the primitive volatile inventory of the LMO, and hence the volatiles that were accreted and retained during lunar formation. This is in contrast to the mare basalts which may record a separate volatile delivery event and are largely affected by magma degassing [7, 12].

2. Analytical method

We measured the OH contents and the H isotopic composition of apatite grains in two representative lunar highland samples from the Mg-suite: troctolite 76535 and norite 78235 of similar crystallisation ages ~ 4.35 Ga [13] and ~ 4.44 Ga [14] respectively. The analyses were performed using the Cameca NanoSIMS 50L ion probe at The Open University. For each analysis a Cs+ beam of ~ 420 pA was used over an area ~ 10 x 10 μm with 25 % electronic gating. Negative secondary ions of ¹H, D, ¹⁸O, ¹³C were collected simultaneously on electron multipliers.

3. Results

Seven analyses of two apatite grains (figure 1 shows one of the grains analyzed) were carried out on sample 76535. Of these only one analysis was above the instrumental limit of detection (~ 28 ppm OH), and yielded an OH content of ~ 50 ppm, with a δD ~ 700 ± 343 ‰ (2 σ). Five analyses were performed on two apatite grains in sample 78235, which yielded OH contents between 400 and 3000 ppm, with a weighted average δD value of ~ 37 ± 94 ‰ (2 σ).

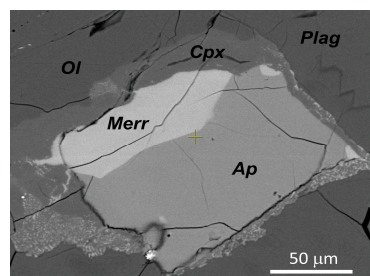


Figure 1: Back scatter electron image of an apatite grain analyzed in 76535. Ap = apatite, cpx = clinopyroxene, merr = merrillite, ol = olivine, plag = plagioclase.

4. Discussion and Conclusions

If considered alone the results for the troctolite 76535 indicate that highlands samples and by extension the early LMO are characterized by low OH - high δD signatures, (a characteristic also reported by [6,11]). However, it is well documented that troctolite 76535 experienced post-crystallization thermal metamorphism and a metasomatic event which altered the rock geochemistry [15]. It has been proposed that the metasomatic agent was a Cl-rich melt which would have de-stabilized any intercumulus apatite in favor of the formation of merrillite [15]. This is in agreement with the textural relationships we observe in our thin section of this rock (figure 1) and electron microprobe studies [15]. Interestingly there does not seem to be a correlation between the cosmic ray exposure age of either sample (~ 215 My for 76535 [ages summarised in 16] and ~ 290 My for 78235 [17]) and the δD results. Furthermore the elevated δD of apatite in the troctolite seems to negate the hypothesis that this sample has seen a significant contribution of solar wind implanted H [9]. It is therefore very likely that the OH - D/H systematics of apatite in the troctolite have been affected by the metasomatic event and therefore preserve a record of that event and not the signature of the primitive LMO cumulates.

In contrast the norite, does not show any signs of alteration and despite being heavily shocked seems to retain its primitive OH - D/H systematics. As such the norite can be used to estimate the H₂O content of the noritic melt at the time of apatite crystallization (between ~ 96 and 99 %). We used an apatite-melt partition coefficient for OH of 0.3 [18]. The calculations suggest that the melt contained ~ 700 to 5000 ppm H₂O when apatite crystallized. We then modeled the amount of H₂O in 1) the primitive noritic melt by “removing” the effect that prior fractional crystallization of nominally anhydrous minerals had on the H₂O content of the noritic melt; 2) in the source region of the noritic melt by calculating the H₂O content for 3 to 20 % degrees of partial melting. Our results indicate that the source region (i.e. the primitive LMO cumulates) for the noritic melt may have contained from 1 to 6 ppm H₂O, implying a wet LMO mantle, which is in good agreement with [10].

The similarity of the H isotopic composition of apatites in the norite (weighted average δD of - 37 ±

94 ‰) and estimates of bulk-Earth δD (~ - 45 ‰ [19]) argues in favor of the volatile inventory of the primordial LMO to have been inherited from the Proto-Earth. This is in agreement with the hypotheses that the Moon accreted largely from Proto-Earth material [e.g. 20]. As mare basalts seem to require “wetter” source regions, this would also be consistent with the late addition of H-bearing species into their source regions towards the end of the LMO crystallization [12].

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