D-poor hydrogen in lunar mare basalts assimilated from lunar regolith

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Abstract

Apatite grains in lunar mare basalts contain hydrogen that ranges in D/H ratio by more than a factor of two. For most of these basalts, the D/H ratios in their apatite grains decrease with measures of the host basalts’ time spent at elevated temperature, specifically the Fe-Mg homogenization of their pyroxenes. Most basalts with homogeneous pyroxenes (i.e., with constant Fe/Mg ratio) have apatite grains with low D/H (δD ≈ −100‰), whereas most basalts with heterogeneous pyroxenes (i.e., varying or zoned Fe/Mg) have apatite with high D/H (δD up to +1100‰). This relationship suggests that low D/H values were acquired during thermal processing, i.e., during Fe-Mg chemical equilibration, during or after emplacement. This light hydrogen is likely derived from solar wind implanted into the lunar regolith (with δD from −125‰ to −800‰), and could enter basalts either by assimilation of regolith or by vapor transport from regolith heated by the flow. If a basalt could not interact with regolith rich in solar wind (e.g., it was emplaced onto other fresh basalts), its apatite could retain a magmatic D/H signature. The high D/H component (in the apatites of unequilibrated basalts) is most reasonably that indigenous magmatic hydrogen, i.e., representing hydrogen in the basalt’s source mantles, or magmatic hydrogen that was residual after partial degassing of H2.

Keywords: Mare basalt, hydrogen isotopes, lunar regolith

Introduction

The inferred abundances of volatile species in the Moon have changed drastically over the last decade—from nearly absent, to as abundant as in the Earth (Saal et al. 2008; Boyce et al. 2010; McCubbin et al. 2010, 2015; Elkins-Tanton and Grove 2011; Greenwood et al. 2011; Hauri et al. 2011; Hui et al. 2013). The inferred abundance of hydrogen is central to this change of view, and hydrogen bears special importance in petrology, astrobiology, and resources for human habitation. Hydrogen has two stable isotopes, hydrogen proper and deuterium, and their abundance ratio D/H is a crucial clue to the histories of volatiles in the Moon and its samples.

The D/H ratio is particularly useful for the Moon because its materials span a huge range in D/H, from essentially zero to six times that of standard seawater—in the common δD notation1 from −900‰ to ~+5000‰ (Liu et al. 2012a; Saal et al. 2013; Tartèse et al. 2014a). Lunar δD values have been measured in many types of materials, including: the mineral apatite, see Figure 1 (Greenwood et al. 2011; Barnes et al. 2013; Tartèse et al. 2014a); igneous glasses and melt inclusions (Saal et al. 2008, 2013; Chen et al. 2015; Hauri et al. 2015); regolith and its agglutinates (Epstein and Taylor 1973; Liu et al. 2012a); and the minerals plagioclase (Hui et al. 2015), pyroxene, and olivine (Liu et al. 2012b). Some of the highest δD values reflect production of D by cosmogenic spallogenesis (Saal et al. 2013; Tartèse et al. 2014a), which is most significant for hydrogen-poor materials (Stephan and Robert 2014; Treiman et al. 2014). After corrections for spallogenic D, lunar δD values still range up to ~+4200‰ (Saal et al. 2013).

The mineral apatite, Ca5(PO4)3(F,Cl,OH), is central to understanding lunar H and other volatiles, because it is widespread (although of low abundance) in lunar rocks and regolith, and is the only currently known crystalline phase on the Moon that requires volatile species. The volatile element compositions of apatite have been used widely as a monitor of volatile element (H, C, F, S, and Cl) abundances and behaviors in geological systems, both planetary (Watson et al. 1994; Boctor et al. 2003, 2010; McCubbin et al. 2010; Greenwood et al. 2011) and terrestrial (O’Reilly and Griffin 2000; Patiño Douce and Roden 2006; Boyce and Hervig 2008, 2009).

Interpretations of this large range in lunar δD in lunar apatite (after correction for spallogenesis) are many and varied, both in terms of processes and components. Components that may contribute to lunar H signatures include: primordial material from Moon formation; residual silicate melt from the lunar magma ocean, i.e., the KREEP component (Tartèse et al. 2014b), com-

1The “δ” notation gives the deviation, in parts per thousand, of the abundance ratio of the uncommon to the common isotope, relative to the abundance ratio of a standard, e.g., δD = \frac{\left[\frac{D}{H}\right]_{\text{sample}} - \left[\frac{D}{H}\right]_{\text{standard}}}{\left[\frac{D}{H}\right]_{\text{standard}}} \times 10^3$, where the standard is VSMOW.