A JOURNEY OF THE MOON'S WATER: HYDROGEN PARTITIONING BEHAVIOR IN THE LUNAR MAGMA OCEAN A. Roy[1], A. Mallik[1], S. Schwinger[2], P. Moitra[1], A. G. Distel[3], R. L. Hervig[3], M. Bose[3], J. J. Barnes[4], and M. R. Guild[3], [1]Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA, [2]Institute of Planetary Research, German Aerospace Center, Berlin 12489, Germany, [3]Arizona State University, School of Earth & Space Exploration, Tempe, AZ 85287, USA, [4]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA; arkadeeproy@arizona.edu

Introduction: Water, or hydrogen, is a vital volatile component on the Moon, just as it is on Earth. Estimating the water content in the bulk silicate Moon (BSM) is important as the initial water content in the Moon dictates the variation in water content among lunar crustal rocks and influences mantle rheology. Changes in rheological properties of the mantle in turn control overturn and convection dynamics. Furthermore, some of the water identified as ice in the permanently shadowed regions of the lunar poles may have originated, at least in part, from volcanic outgassing [1] and this fraction is not well constrained. Placing constraints on the lunar water content allows us to understand the ancient giant impact event, contributions by later impactors, and planetary-scale differentiation processes. This Moon-forming giant impact was pivotal in fractionating volatiles within the Earth-Moon system, leading them along their unique evolutionary trajectories.

Post-Apollo-era investigations [2] concluded that the BSM contains less than 1 ppb H_2O. These findings were largely attributed to the general absence of liquid water, hydrated minerals, and lack of unique isotopic signatures specific to the Moon. However, advances in mass spectrometry and techniques for measuring trace amounts of water first in volcanic glass beads, melt inclusions, apatite, and later in nominally anhydrous minerals (NAMs) have challenged these results [3-8]. Over the past 15 years, hydrogen has been detected in diverse materials within the Apollo sample collection, including plagioclase grains in ferroan anorthosites (FANs) [3,4], olivine-hosted melt inclusions [5], picritic glass beads [6], apatites [7,8], and granite clasts [9]. A recent review study [10] that revisited these Apollo-sample analyses predict the water content for the BSM to range from 1.38 to 74 ppm. This variability can be attributed to the factors [11]: (i) variations in magma ocean model conditions, and (ii) poorly constrained water partition coefficients.

Background: The giant impact that formed the Moon resulted in extensive melting of its interior-canonically referred to as the lunar magma ocean (LMO). The hydrogen partition coefficient (D_H) — defined as the ratio of hydrogen (or water) content in a crystallizing mineral to that in the corresponding magma - is a key parameter for tracing the progressive evolution of melt and mineral water contents during the solidification of the LMO.

A wide range of D_H values can lead to significantly different estimates of the Moon's water content [11]. The higher D_H values result in a drier LMO (with an initial bulk H_2O content of ~10 ppm), while lower D_H values exhibit a much wetter LMO (with initial bulk H_2O content ranging from 100 to 1000 ppm). The uncertainty in D_H primarily stems from the unique conditions expected within the LMO, which include a reduced redox state relative to typical terrestrial magmas [12] and the prevalence of highly iron- and titanium-rich mineralogies. The D_H for minerals crystallizing under such reduced conditions has remained poorly constrained. We seek to close the gaps in our understanding of the water content of the BSM through petrologic experiments aimed at determining LMO-relevant D_H values.

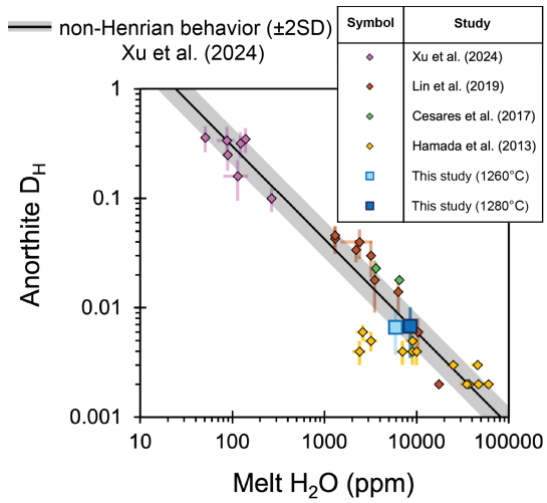


Figure 1. *Hydrogen partition coefficient (D_H) of anorthite versus glass (or melt) water content. Partitioning behavior is noted to be non-Henrian across literature data [13-16]. Errors are in 1-σ.*

Methods: We conducted high pressure-temperature experiments using a piston-cylinder apparatus to determine the D_H of minerals crystallizing under conditions analogous to the lunar magma ocean (LMO). These 48-hour experiments were performed at 1260–1280°C and 0.5 GPa in a graphite capsule, which provided a reduced environment for the late-stage magma ocean composition LPUM88/HA02-5 [17]. H content in various phases was measured as $^{16}O^{1}H^{-}/^{30}Si^{+}$ using a Cs^{+} primary beam on secondary ion mass spectrometry (SIMS) and nano-SIMS instruments.

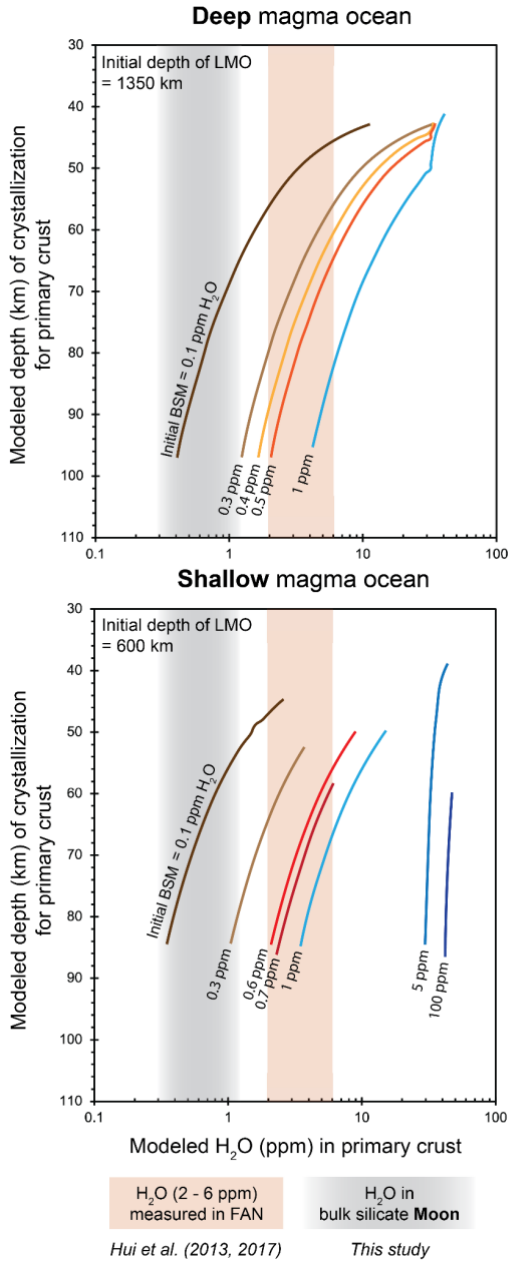


Figure 2. *H_2O in the FAN (ferroan anorthosite suites) modeled as a function of depth of crystallization by varying (a) initial BSM water content, and (b) depth of LMO. Range of water contents measured in the FAN [3,4] and our calculation for the BSM are marked.*

The D_H values calculated from our experiments were used in a LMO crystallization model to investigate their sensitivity. The LMO crystallization model uses a combination of alphaMELTS and FXMOTR (from SPICES software package) along with appropriate H_2-H_2O solubility laws [18,19]. The initial depths of LMO scenarios modeled range from 600 – 1300 km. Degassing from the magma ocean is assumed to have halted once the plagioclase appears on the liquidus i.e., crust building was initiated.

Results and Discussion: The experiments, representative of shallow LMO conditions, produced a phase assemblage consisting of anorthitic plagioclase, Fe-rich augite, ilmenite, silica, and glass (or melt). The calculated oxygen fugacity (fO_2) of these experiments is ~ ΔIW + 1. SIMS analyses of silica polymorphs, the first of its kind from a Fe-rich basaltic melt, and the corresponding melt pools reveal D_H ranging from 0.013 - 0.021 (when glass water contents are between 5,250 and 6,150 ppm). D_H values of anorthite are between 0.0066 and 0.0068 for glass water contents ranging between 5,000 and 12,000 ppm. This result (Fig. 1) is consistent with the expected non-Henrian behavior of hydrogen incorporation wihtin anorthite [13]; i.e., the hydrogen partitioning behavior is strongly controlled by the water content of the melt.

The LMO crystallization modeling results are compared to the water content (0.2 – 0.6 ppm) measured in FANs [3,4], assumed to be the primary derivatives of the LMO. To justify this water content, the BSM must have ~ 0.3 – 1 ppm initial water budget (Fig. 2), close to that predicted by recent studies [10, 20]. Once the D_H values are narrowed down, these estimates hold across shallow to deep LMO scenarios. We conclude that the BSM is drier than the Earth's upper mantle which has 50 - 200 ppm H_2O [21].

Further investigations will include varying the degassing rate from the LMO and partition coefficients for minerals like olivine and pyroxenes, which will shed more light on the "wetness" of the lunar mantle.

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