

APATITE IN ALLAN HILLS 81005 AND THE ORIGIN OF WATER IN THE LUNAR MAGMA OCEAN.

K. L. Robinson^{1,2}, J. J. Barnes^{3,4}, R. Tartèse³, L. J. Hallis², I. A. Franchi³, M. Anand^{3,4} and G. J. Taylor^{1,2}, ¹Hawaii Institute of Geophysics and Planetology, 1680 East-West Rd., Honolulu, HI 96822. ²UHNAI, ³Planetary and Space Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK. ⁴Department of Earth Sciences, The Natural History Museum, Cromwell Road, London, SW7 5BD, UK. krobinson@higp.hawaii.edu

Introduction: Following the discovery of water in glasses, apatites, and melt inclusions derived from the lunar interior [1-3], the idea that the Moon is an anhydrous planetary body is being rewritten. Water in the interior could have either been accreted with the Moon-forming material [4] or been added very early in the Moon's history [5], and it might have played a role in lunar differentiation.

The amount of water that was present in the lunar magma ocean (LMO) and the fate of that water during LMO crystallization are currently uncertain. Measurements of pre-eruptive water content of some lunar magmas through melt inclusions, preserved in olivine in pyroclastic glass beads [3], suggests that at least part of the lunar interior is as wet as the depleted MORB source in the terrestrial upper mantle, containing ~ 100 ppm of H₂O. To produce mantle cumulates with such a level of H₂O requires that the LMO contained 100-1000 ppm H₂O [6]. In principle, water behaves like an incompatible element and would have concentrated in the melt, reaching very high concentration in the last few percent of the residual LMO, i.e. urKREEP. However, reconciliation of measured H isotope and water content data from apatites in a variety of lunar rocks may ultimately require a diversity of water reservoirs in the lunar interior [7-11]. Apatite in mare basalts generally contains more water than in evolved, KREEPy rocks or most Mg-suite rocks [7-11]. Yet all of these measurements come from lithologies that were derived from LMO products, rather than being a product of crystallization of the LMO itself. Knowing the H₂O content, and its H isotopic composition, of the LMO would help our understating of the amount and sources of water in the primitive Moon.

The ferroan anorthosites (FANs) are thought to represent the original plagioclase flotation crust that crystallized out of the LMO [12,13]. Fourier Transform Infrared (FTIR) spectroscopic measurements of water in nominally anhydrous plagioclase from FAN samples have been interpreted as indicating that the initial LMO contained 320 ppm H₂O [14]. However, when this estimate is extrapolated, it indicates that the LMO urKREEP residue contained up to 1.4 wt.% H₂O [14]. This seems to be in disagreement with the analyses of apatite in KREEP-rich samples [7]. Plagioclase does not readily incorporate water and hydrous minerals such as apatite are very scarce in FAN rocks. Here we

present the first apatite water content and H isotope results from an apatite-rich FAN-like lithology from meteorite Allan Hills A81005 (ALHA 81005) [15].

Sample Description: ALHA 81005 is a complex anorthositic regolith breccia [16]. Goodrich et al. [15] described an unusual apatite-rich anorthositic troctolite in ALHA 81005 (Fig.1). This lithology seems to be related to the ferroan anorthosites and could be a magma ocean product [15]. The lithology is clearly unrelated to other major suites of lunar rocks (mare basalts or the Mg- and alkali-suite rocks), although the details of its petrogenesis are obscure.

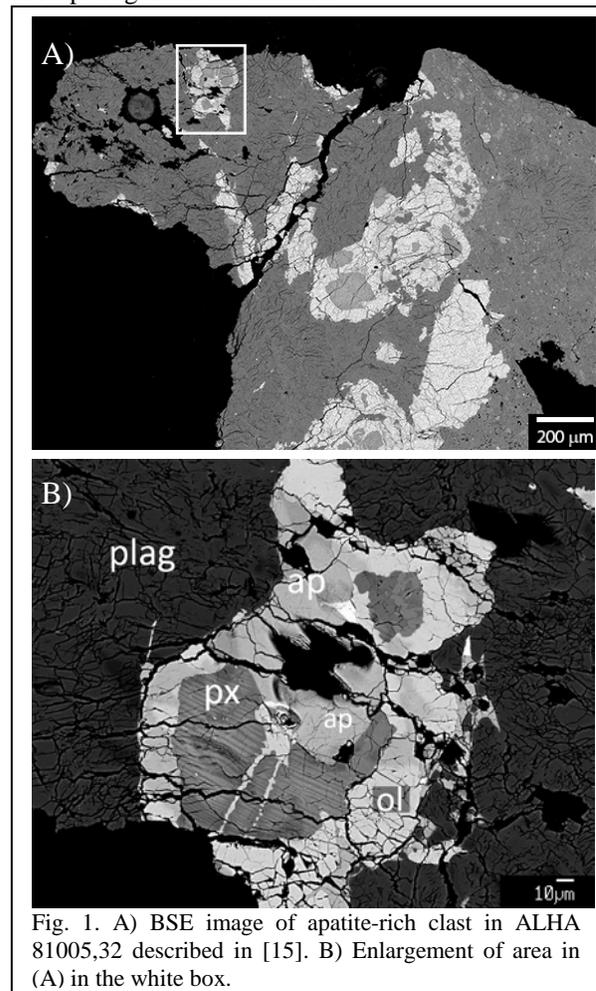


Fig. 1. A) BSE image of apatite-rich clast in ALHA 81005,32 described in [15]. B) Enlargement of area in (A) in the white box.

Lithology: A detailed description of the apatite-rich lithology discussed in this abstract and four scenarios accounting for its petrogenesis are presented in [12].

The clasts consist of exsolved pyroxene rimmed by Fe-rich olivine, all enclosed within plagioclase (Fig. 1). Some of the pyroxene and apatite have been resorbed [15]. Apatite and whitlockite are both present, though their crystallization order relationship with the olivine is not always clear. Apatite seems to have crystallized at the same time as pyroxene [15]. Plagioclase chemistry (average molar An versus Mg/(Mg+Fe)) puts it in the ferroan anorthosite field [15].

Methods and Results: Water content and H isotope measurements were performed using the Cameca NanoSIMS 50L at The Open University following the protocol described elsewhere for analysis of lunar meteorites [10]. Data reported here have not been corrected for spallogenic production of H and D, which was insignificant due to the young cosmic-ray exposure age of ALHA 81005 (< 5 Ma [17]). We analyzed eight spots on three different apatite grains in ALHA 81005,32. All apatites measured have low to moderate water contents ranging from 65 to 568 ppm H₂O. Corresponding δD values range from -292 to 167 ‰ (Fig. 2), giving a weighted average δD value for ALHA 81005 apatites of -73 ± 140 ‰, which is well within the range for the Earth's upper mantle (-140 to +60 ‰ [20 and references therein]). This is much lower than for most Apollo samples, except for norite 78235 [11], and a KREEP basalt differentiate [18].

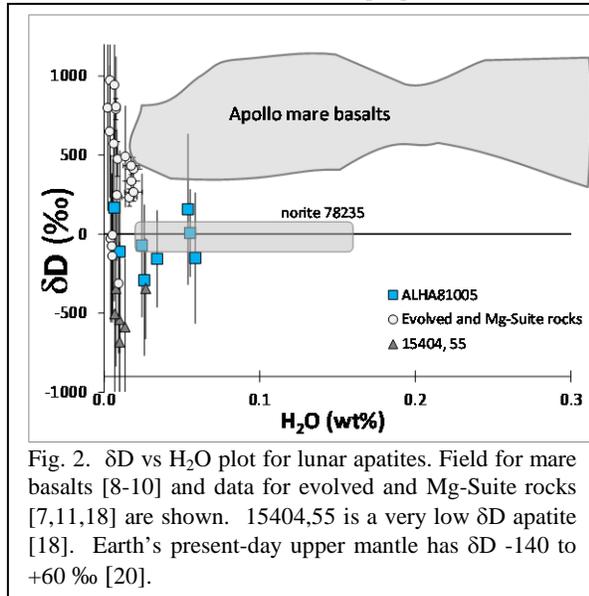


Fig. 2. δD vs H₂O plot for lunar apatites. Field for mare basalts [8-10] and data for evolved and Mg-Suite rocks [7,11,18] are shown. 15404,55 is a very low δD apatite [18]. Earth's present-day upper mantle has δD -140 to +60 ‰ [20].

Discussion: The apatite analyzed in ALHA 81005 contain ~ 65 to 568 ppm H₂O (Fig. 2). Using apatite/melt partition coefficients of 0.1 and 0.25 [2,19], this implies ~ 260 to 5700 ppm H₂O in the magma when apatite crystallized.

If this unique clast did indeed form in the LMO, through local magma mixing or reaction with pre-existing cumulates [15], the LMO would have achieved

~ 80 % crystallization (roughly the time plagioclase is expected to start crystallizing [e.g., 21]), hence the LMO could have contained ~ 50-1100 ppm H₂O before it started to crystallize (considering extreme end-member of pure fractional crystallization). This might be a reasonable upper limit for the amount of H₂O in the initial LMO, especially considering the small amounts of water in KREEP-rich lithologies [7,18].

The most important observation is that the δD of the apatite-rich clast in ALHA 81005 is within the range of δD estimated for the present-day Earth's upper mantle [20], both having δD signatures comparable to that of some carbonaceous chondrites [22]. Considering that this clast in ALHA 81005 is a magma ocean product, the terrestrial-like δD suggests that the Moon and Earth had similar sources for their water, and that there was little hydrogen isotopic fractionation during formation of the Moon. The ALHA 81005 clast is petrologically complicated and its origin as a magma ocean product is far from certain. Nevertheless, regardless of its origin, it was clearly derived from a reservoir inside the Moon that had water with a hydrogen isotopic composition similar to that of terrestrial mantle.

Acknowledgements: This research was supported by NASA Astrobiology Institute CAN NNA09DA77A and LASER NNX11AE85G. This work was partially funded by a STFC research grant to MA (Grant no. ST/I001298/1).

References: [1] Saal A.E. et al. (2008) *Nature*, 454, 192-195. [2] McCubbin F.M. et al. (2010) *PNAS*, 107, 11223-11228. [3] Hauri E.H. et al. (2011) *Science*, 333, 213-215. [4] Saal A.E. et al. (2013) *Science*, 340, 1317-1320. [5] Tartèse R. and Anand M. (2013) *EPSL*, 361, 480-486. [6] Elkins-Tanton L.T and Grove T.L. (2011) *EPSL*, 307, 173-179. [7] Robinson K.L. et al. (2013) *LPS XLIV*, Abstract #1327. [8] Greenwood J.P. et al. (2011) *Nature Geosci.*, 4, 79-82. [9] Barnes J.J. et al. (2013) *Chem. Geo.*, 337-338, 48-55 [10] Tartèse R. et al. (2013) *GCA*, 122, 58-74. [11] Barnes J.J. et al. (2013) *EPSC*, Abst. #105. [12] Wood J.A. et al. (1970) *Proc. All Lunar Sci. Conf.*, 965-988. [13] Shearer C.K. and Papike J.J. (1999) *Am. Mineral.*, 84, 1469-1494. [14] Hui H. et al. (2013) *Nature Geosci.*, 6, 177-180 [15] Goodrich C. A. et al. (1985) *Proc. 15th Lunar Planet. Sci.*, C405-C414. [16] Warren P.H. et al. (1983) *GRL*, 10, 779-782. [17] Tuniz C. et al. (1983) *GRL*, 10, 804-806. [18] Robinson K. L. et al. (2014), *LPS XLV*, Abst. #1607. [19] Mathez E.A. and Webster J.D. (2005) *GCA*, 69, 1275-1286. [20] Hallis L.J. et al. (2012) *EPSL*, 359-360, 84-92. [21] Snyder G.A. et al. (1992) *GCA*, 56, 3809-3823. [22] Alexander C.M.O'D. et al. (2012), *Science*, 337, 721-723.