WATER ON THE MOON: INSIGHTS FROM NOMINALLY ANHYDROUS MINERALS IN THE LUNAR BASALTIC BRECCIA METEORITE ELEPHANT MORaine 87521. A. G. Distel1, J. Davidson1,2, M. Wadhwa1 and R. L. Hervig1. 1School of Earth and Space Exploration (SESE), Arizona State University, USA (agdistel@asu.edu). 2Buseck Center for Meteorite Studies, SESE, Arizona State University, USA.

Introduction: The hydrogen isotope compositions of planetary materials can indicate where their volatile components originated in the Solar System and aid in understanding magmatic processes involved in their formation ([1–7] and references therein). Studies of water in lunar samples have primarily focused on melt inclusions in nominally anhydrous minerals (NAMs) and late-formed minerals, such as apatite [e.g., 1, 2]. Since NAMs are the first to crystallize from a melt, they are more likely to preserve the original characteristics of magmatic water than later formed minerals [e.g., 4–7]. We are studying NAMs in lunar samples to understand the variability seen within and between lunar samples and to provide further insights into the origin of the Moon’s water and lunar petrogenesis. Here we report H isotope compositions and water concentrations of nominally anhydrous pyroxene and olivine in the lunar basaltic breccia meteorite Elephant Moraine (EET) 87521.

EET 87521 is a very low-Ti (VLT) lunar basaltic breccia with a total known weight of 30.7 grams. It contains pyroxenes up to 1.2 mm in diameter that range in major element compositions from En5–W05–10 to En30–W015–40 [8]. Olivines in EET 87521 range in major element compositions from Fo65 to Fo5 [8]. EET 87521 may be paired with EET 96008, which we previously studied [9, 10]. EET 87521 was chosen for study as it has a relatively low cosmic ray exposure age of ~26–50 Ma [11, 12], thereby requiring minimal correction for cosmogenic deuterium, and a low weathering grade of < 2 [8], potentially limiting the effects of terrestrial weathering.

Methods: An interior, fusion-crust free chip of EET 87521 was co-mounted with terrestrial standards in indium metal in a one-inch aluminum disc. Anhydrous sample preparation techniques were utilized [3, 5, 6]. Mineral major element compositions, element mapping and high-resolution secondary and backscattered electron (BSE) imaging were undertaken on a JEOL JXA-8530F electron probe microanalyzer (EPMA) at Arizona State University (ASU). Hydrogen isotope compositions (δD in per mil) and water concentrations (H2O in µg/g) were determined via secondary ion mass spectrometry (SIMS) on the Cameca IMS-6f at ASU following analytical protocols similar to those of [5, 6]. The H2O concentrations were estimated using a H2O/µg calibration curve on terrestrial standards (PMR 53 pyroxene and KBH-1 [13, 14]). A background H2O concentration of 11 µg/g and H isotope ratio of approximately δD = −100‰ were determined by analyzing dehydrated PMR 53 pyroxene throughout the analytical session, and were corrected for by the methods of [15] and [16], respectively. We also corrected for instrumental mass fractionation, which was monitored throughout the analytical session on the pyroxene standards PMR 53 and KBH-1 [13, 14].

Results: We analyzed thirteen pyroxenes (Fig. 1) ranging in diameter from ~130 to ~655 µm with a range of major element compositions (Wo11–34En13–61Fs24–65). The H isotope compositions of these pyroxenes range from δD = −512 ± 90‰ to +8 ± 67‰ and H2O contents range from 19 ± 4 µg/g to 118 ± 24 µg/g (n=15). The pyroxene with the highest H2O content corresponds to a δD of −51 ± 31‰ and major element composition of Wo26En30Fs26 (Fig. 2). While there were small intragrain variations in major element compositions, they did not correlate with observable variations in H isotope compositions or H2O concentrations. For example, one pyroxene grain (Px14) ranged in major element composition from Wo20En22Fs56 to Wo26En24Fs57, with δD of −360 ± 46‰ to −330 ± 80‰ and H2O contents of 54 ± 11 µg/g to 71 ± 14 µg/g (n=2).

We also analyzed five olivines (Fig. 1) ranging in diameter from ~120 to 650 µm and in composition from Fo5 to Fo80. Two olivines did not contain detectable H2O. The H isotope compositions of the other three olivines ranged from δD = −265 ± 93‰ to −137 ± 51‰ and H2O contents ranged from 19 ± 4 µg/g to 63 ± 13 µg/g.
Figure 2. H isotope composition (as δD in per mil, ‰) versus water concentration (H₂O in µg/g) for pyroxenes and olivines in EET 87521 compared with pyroxenes from EET 96008 [9]. Error bars are 2σ.

Discussion: There is no apparent correlation between H₂O and δD in NAMs from EET 87521 in this study or in NAMs from our previous study of EET 96008 [9] (Fig. 2). The EET 87521 pyroxene grains are generally isotopically lighter and significantly drier than those we analyzed in the potentially paired lunar basaltic breccia EET 96008 (δD = −82 ± 35 ‰ to +259 ± 108 ‰ and H₂O contents of 11 ± 2 µg/g to 403 ± 81 µg/g [9]) (Fig. 2). Given the fact that they were prepared using similar methods, this difference suggests that they may not be paired, as may also be indicated by their somewhat different terrestrial residence ages (EET 87521: 15–50 ka [11]; EET 96008: 80±30 ka [17]). Specifically, it is possible that the more significant terrestrial exposure and contamination of EET 96008, as indicated by its somewhat longer terrestrial residence age, resulted in its pyroxenes having higher H₂O concentrations (Fig. 2).

While some of the NAMs from EET 87521 have δD compositions within the range inferred for indigenous lunar water (δD from −200 to +200 ‰ [2]), many are isotopically lighter. This may be due to secondary processes such as terrestrial weathering, shock, or cosmic ray exposure.

Despite the low weathering grade of EET 87521, we cannot eliminate the possibility of terrestrial contamination during its residence in Antarctica. While the H₂O concentrations in many of the EET 87521 pyroxenes analyzed here are <50 µg/g, some of them are higher (Fig. 2), it is possible that these higher concentrations may have resulted from minor terrestrial contamination. The hydrogen isotope composition of Standard Light Antarctic Precipitation 2 is δD = −427.5 ‰ [18]; the H isotope ratios of EET 87521 pyroxenes are typically heavier than this (Fig. 2). Nonetheless, it is possible that some of the lightest δD measured in EET 87521 pyroxenes could be the result of terrestrial alteration.

Shock glass is present within EET 87521, consistent with shock pressures of ~20–30 GPa [12,19]. Although the effects of shock in pyroxenes are not well documented, shock processes are known to increase δD in other phases [2]. Therefore, shock cannot likely explain the isotopically light δD measured in EET 87521 pyroxenes. The shock pressures that EET 96008 experienced are not well constrained, and further research is needed to determine if shock could cause the differences observed for EET 87521 and EET 96008.

Cosmic ray exposure (CRE) can also increase δD by introducing cosmogenic D through spallation reactions [2]. Since CRE increases δD, it is not a likely explanation for the isotopically light H observed for EET 87521 NAMs. Additionally, CRE cannot explain the differences between EET 87521 and EET 96008 as they have similar CRE ages [11,12,17].

The implantation of solar wind (~δD = −1000 ‰) into lunar regolith can also affect the primary hydrogen isotope signature by decreasing the δD compositions [2,20]. The mixing of basaltic melts with lunar regolith has been documented [2,20], and could explain the isotopically light H isotope compositions seen in NAMs from EET 87521.

Conclusions: The low δD compositions for EET 87521 could be explained by mixing with solar wind-rich lunar regolith, a contribution from terrestrial water in Antarctica, or both. To further investigate these possibilities, we will perform future analyses on NAMs in Apollo samples, which are assumed to have remained unaltered since their collection on the Moon.

Acknowledgements: This work was funded by NASA Solar System Workings grant 80NSSC21K0181 (PI: M.W., CoI: J.D.).