TESTING THE urKREEP- δ^{37}Cl HYPOTHESIS WITH EUCRITES. Una G. Schneck [1], Jeremy W. Boyce[1], Allan Treiman[2], John M. Eiler[3], Yunbin Guan[3], Chi Ma[3]. [1]Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90095; [2]Lunar and Planetary Science Institute, Houston, TX 77058; [3]Division of Geological & Planetary Sciences, California Institute of Technology, Pasadena, CA 91125.

Introduction: Measurements of chlorine isotopes in lunar apatite ($Ca_5[PO4]_3[F,Cl,OH]$) include δ^{37}Cl values between -4‰ and +81‰, which is more variation than the rest of the solar system combined [1]. Originally, values greater than 0‰ were attributed to the degassing of H-free basalts during eruption [2], but more recent work has suggested it could instead be an indicator of planet-wide magma ocean degassing [3]. If the fractionation of chlorine was only related to the loss of Cl, we would expect high δ^{37}Cl to be associated with low Cl abundance, but instead a positive correlation is observed between δ^{37}Cl and Cl abundance in apatite. Boyce et al. (2015) [3] also noted positive correlations

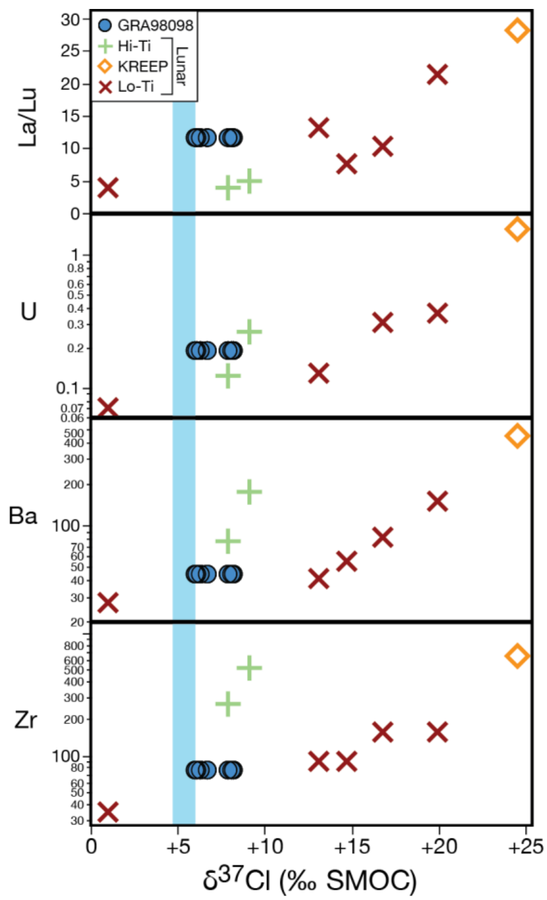

Fig. 1. δ^{37}Cl versus trace, incompatible elements which are elevated in urKREEP preserved in lunar basalts [3 and references therein] and vKREEP in non-cumulate eucrites (GRA 98098 and NWA 3147, this study). Because we lack trace element data for NWA 3147, it is plotted as a blue bar.

between bulk Th, bulk La/Lu, and δ^{37}Cl, which they interpreted as indicating a shared reservoir in lunar basalts that contains elevated incompatible element abundances and also elevated δ^{37}Cl. If isotopically lighter Cl species are lost preferentially during magma ocean degassing, then the residual, isotopically heavier δ^{37}Cl would be concentrated in the last remnants of the lunar magma ocean (the urKREEP), which also has elevated incompatible element abundances, as well as elevated La/Lu [4,5]. As shown by Fig. 1, this is true not only for Th and La/Lu, but for several other elements that would be preferentially enriched in the urKREEP. The relationship between δ^{37}Cl and urKREEP implies that high δ^{37}Cl may be formed during the degassing of the lunar magma ocean.

If high δ^{37}Cl is a ubiquitous feature of magma oceans—or even just for magma oceans on smaller bodies which we would expect to be more easily degassed than larger bodies—then we would expect to observe the same correlations in other small bodies thought to have magma ocean phases. The most obvious test of this hypothesis is provided by the HED meteorites from the asteroid 4Vesta. It is believed that 4Vesta had a magma ocean in its past [6], and previous workers have pointed to the possible existence of a "vestan KREEP" (a.k.a. vKREEP [7]) that would have formed under a similar evolutionary history as lunar urKREEP. If vKREEP is chemically analogous to the lunar urKREEP, then we would predict that it exhibits a comparable δ^{37}Cl fractionation. To test this hypothesis, we analyzed eucritic apatite from two basaltic meteorites from 4Vesta: GRA 98098 and NWA 3147.

Samples*:* GRA 98098 and NWA 3147 are non-cumulate eucrites. They are representative of the upper, basaltic vestan crust and are the most promising candidates for retaining the igneous history of 4Vesta [7,8]. In addition, GRA 98098 and NWA 3147 are both *Stannern Trend* eucrites, which are characterized by elevated levels of trace incompatible elements [10]. The apatite grain size in the selected eucrites varied between approximately 1 and 20 µm (e.g. Fig. 2).

Methods: Apatite grains were identified by electron probe WDS X-ray mapping and SEM-EDS. Then, following protocols outlined in [10], measurements of the $^{37}Cl/^{35}Cl$ isotope ratio from polished thin-sections were analyzed using Secondary Ion Mass Spectrometry (SIMS) at the California Institute of Technology. Durango apatite ($\delta^{37}Cl$ = +0.40‰ relative to standard mean ocean chlorine) was used as a standard.

Results and Discussion: Unlike terrestrial basalts, both GRA 98098 and NWA 3147 exhibit notably heavy $\delta^{37}Cl$. GRA 98098 has $\delta^{37}Cl$ values ranging from +6‰ to +8.2‰ while NWA 3147 ranges from +4.7‰ to +6‰ relative to standard mean ocean chlorine (SMOC).

These values are appreciably similar to lunar basalts and heavier than all other published $\delta^{37}Cl$ analyses from meteorites except for a single analysis of the martian meteorite NWA 7034 [11]. This is consistent with the prediction made in [3], and supports the hypothesis that $\delta^{37}Cl$ anomalies can be generated during magma ocean degassing.

Both eucrites show better intra-sample reproducibility than lunar samples with multiple analyses, made under under the same conditions, in the same laboratory. Sharp et al. [1] noted large differences between $\delta^{37}Cl$ in the soluble and insoluble portions of bulk lunar samples, as well as between bulk and in situ analyses. We suggest that this indicates a greater degree of $\delta^{37}Cl$ equilibrium within the eucrite samples, a conclusion that should be reaffirmed by bulk analysis of soluble and insoluble portions of eucrites, as well as additional in situ analyses.

For GRA 98098, available bulk chemical data [11,12] allow us to add the new eucrite $\delta^{37}Cl$ data to Fig 1. We observe that GRA 98098 falls along the lunar trend for trace elements believed to be concentrated in the lunar urKREEP. Analysis of additional trace element enriched eucrites as well as trace element impoverished eucrites will permit a full test of the hypothesis that vKREEP is the reservoir of heavy Cl on 4Vesta.

If Cl isotope fractionation is a robust indicator of magma ocean degassing, then we might expect to see elevated $\delta^{37}Cl$ on both the Earth and Mars. The existence of one analysis at $\delta^{37}Cl$ = +9‰ [11] for NWA 7034 suggests that Mars may preserve this reservoir, and that additional observations of martian meteorites will find more heavy chlorine.

However, there are two additional possibilities that we must consider. First, it is possible that conditions are somehow unfavorable to Cl-fractionation on larger bodies. This could be due to incomplete degassing or atmospheric retention that prevents Cl-loss from the system. Second, it could be that there has been Cl isotope fractionation on the Earth and Mars, and that the initial Cl isotopic composition of the material making up the terrestrial planets was < 0‰, as suggested by [14]. The lack of variations on Earth may simply be the result of efficient mixing by plate tectonics.

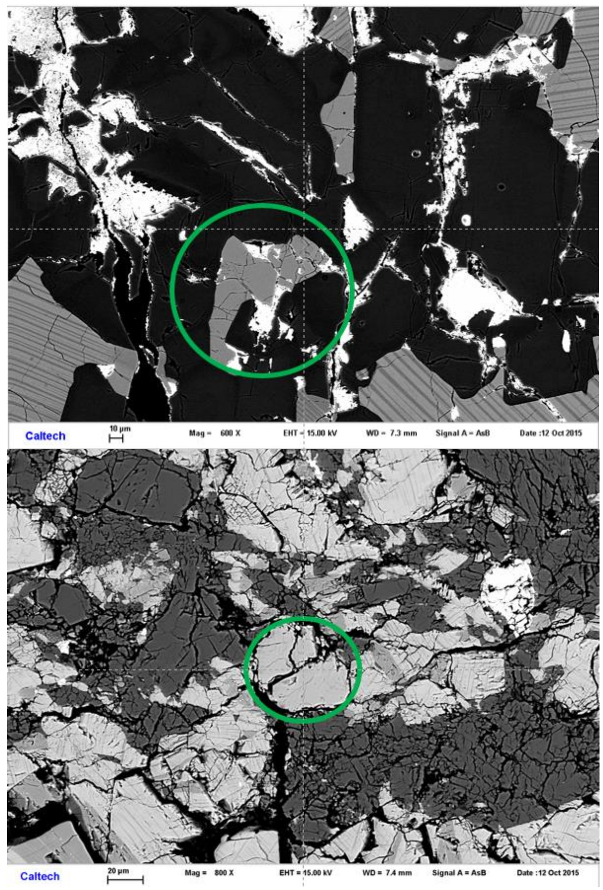

Fig. 2. Upper: Electron backscatter image of typical apatite grain in GRA 98098, analyzed for $\delta^{37}Cl$. Lower: Electron backscatter image of analyzed apatite grain in NWA 3147.

References: [1] Sharp, Z. D. et al. (2010) *Science*, *329*, 1050-1053. [2] Sharp, Z. D. et al. (2013) *Earth & Planetary Science Letters*, *380*, 88-97. [3] Boyce, J. W. et al. (2015) *Science Advances*, *1*, 8 e1500380. [4] Warren, P. H., and Wasson, J. T. (1979) *Reviews of Geophysics & Space Physics*, *17*, 73-88. [5] Neal, C. R. and Taylor, L. A. (1989) *Geochimica et Cosmochimica Acta*, *53*, 529-541. [6] Righter, K. and Drake, M.J., MAPS *32*, 929-944. [7] Barrat, J. A. et al. (2012) *Geochimica et Cosmochimica Acta*, *99*, 193-205. [8] Mittlefehldt, D. W. and Lee M. T. (2001) *Meteoritic & Planetary Science*, *36*, A136. [9] Barrat, J. A. et al. (2007) *Geochimica et Cosmochimica Acta*, *71*, 4108-4124. [10] Sarafian, A. R. et al. (2013) *Meteoritics & Planetary Science*, *48*, 2135-2154. [11] Sharp, Z. D. et al. (2014) *LPSC LVII, Abstract # 1777.* [12] Warren, P. H. et al. (2009) *Geochimica et Cosmochimica Acta*, *73*, 5918-5943. [13] Mayne, R. G. et al. (2009) *Geochimica et Cosmochimica Acta*, *73*, 794-819. [14] Sharp, Z. D. et al. (2014) *LPSC LVII, Abstract # 1617.*