# AN EARTH-LIKE HYDROGEN ISOTOPIC COMPOSITION OF VESTA AS REVEALED BY APATITE.

A.R. Sarafian[1]*, H.R. Marschall[1], S.G. Nielsen[1], F.M. McCubbin[2], and B. Monteleone[1]; [1]Woods Hole Oceanographic Institution, Woods Hole, MA 02540; [2]Institute of Meteoritics, University of New Mexico, Albuquerque NM, 87131 (asarafian@whoi.edu*)

**Introduction:** The relative abundances and concentrations of volatiles in planetary bodies is important because it has the potential to help determine the sources and distribution of water in the Solar System. The howardite-eucrite-diogenite (HED) parent body is particularly interesting in this regard because it is thought to be volatile-depleted [1] and thus it is important to determine how and when this volatile depletion occurred and how it translates to the concentration of the most volatile element, hydrogen. Apatite, a volatile-bearing (F, Cl, OH) mineral, is a minor constituent of eucrites and can give insights into the volatile composition of this parent body, inferred to be Vesta. We used textures, phase associations, $H_2O$ abundances, and isotopic ratios (D/H or δD) of eucrite apatites to help constrain the characteristics of the eucrite source region. Basaltic eucrites (Stannern, Pasamonte, Juvinas, and PCA 91078) were selected because it is difficult to glean parental melt concentrations from cumulates. Furthermore, F, Cl, and computed $H_2O$ concentrations were previously measured by EPMA for several basaltic eucrite samples.

**Methods:** The Cameca IMS 1280 ion probe at the Woods Hole Oceanographic Institution was used to measure $H_2O$ concentrations and the D/H ratio. A $Cs^+$ primary beam was rastered (~10μm x 10μm) and field apertures were used to collect from the center of the secondary ion beam (~5μm x 5μm) to reduce crater edge effects and background; additionally electronic gating was used to further reduce background. Negative ions $^{17}O$, $^{16}O^1H$, and $^{16}O^2H$ were collected. A mass resolving power of ~9400 was used, enough to separate $^{18}O$ from $^{16}O^2H$. Several, previously characterized, apatites were used as $H_2O$ concentration and D/H reference materials [2, 3]. Plagioclase, which was determined to have undetectable OH by FTIR, was used as an instrumental blank on each of the unknown mounts. Only apatites that were inferred stoichiometric, i.e., apatites that had the appropriate amount of $H_2O$ compared with apatites from the same meteorite with measured F and Cl concentrations by EPMA were considered after ion probe analysis.

Raw D/H ratios were corrected for influence from instrument blank, which has an isotope composition of δD = 1008 ±136 ‰ (2SE; n=8) (δD = [(D/H$_{unknown}$) / (D/H$_{standard}$)-1]*1000 ‰) based on water-free plagioclase. These corrections caused our data to shift

between -138 and -17 ‰. A second possible contaminant was the epoxy (δD = -166 ±22 ‰) used to mount all samples except for Cachari, which was mounted in indium metal. Epoxy contains a large amount of hydrogen and could thus affect the D/H measurements. However, for all reported apatites the water content measured by ion probe agrees well with the stoichiometrically calculated content based on EPMA F and Cl contents. We would not have obtained stoichiometric water abundances if epoxy had contributed substantial amounts of water to the D/H measurements. Significant epoxy contamination to our D/H measurements can therefore be excluded. In addition, the H isotopic composition of the epoxy is very close to that of the apatites, rendering epoxy-related corrections insignificant compared with propagated measurement errors.

**Results:**

*Apatite occurrence.* Apatites in Pasamonte, Stannern, Cachari, and PCA 91078 were present in late stage mesostasis [4] and apatites analyzed in Juvinas were present within Fe-rich olivine and pyrrhotite/silica veins similar to those reported by [5].

*Apatite composition.* The apatite $H_2O$ content spans a broad range, while the δD value does not vary significantly (Fig. 1&2). Apatites with different textural contexts do not have significantly different δD values.
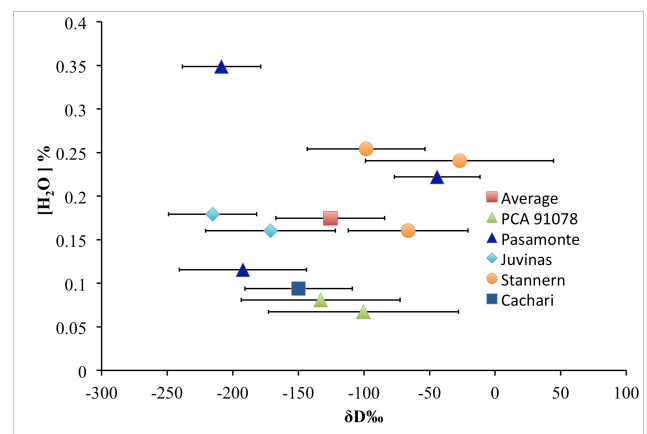


*Figure 1. $H_2O$ content vs δD. Note little variation in δD with large change in $H_2O$ content of apatite. Error bars are 2SE internal error.*
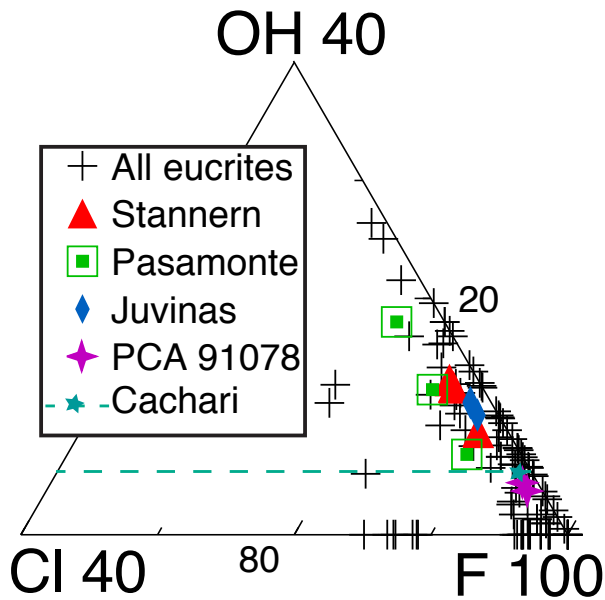
*Figure 2. F-apex of the F-Cl-OH ternary diagram of anion site in apatite. Cachari has not been measured for F and Cl, thus it could lie anywhere on the teal line, but it probably lies close most other eucrites near the teal star. "All eucrite" data are from [4] and rest is new EPMA data. Note, apatites measured here have a similar composition to eucritic apatites measured by EPMA.*

**Discussion:**

There are two simple magmatic mechanisms to cause a variance of $H_2O$ concentrations in apatite: one is to begin the apatite crystallization with OH-poor apatite progressing towards more OH-rich apatite, because $D_F^{ap}/D_{OH}^{ap} > 1$; the second way is to crystallize relatively OH-rich apatite at an early stage, then degas the magma and crystallize OH-poor apatite, because $H_2O$ degasses preferentially over F [6]. The former mechanisms appear to be more likely, because the δD does not correlate with water content (Fig. 1) whereas degassing would cause a kinetic isotope fraction resulting in heavier isotope composition at lower $H_2O$ contents.

Another key observation is the uniform δD of all analyzed samples. The δD is uniformly light compared to measured apatites from the Moon and Mars. The homogenous δD in eucritic apatites that clearly crystallized at different times (veins vs. different mesostasis) is indicative of the fact that the D/H of the parent magmas did not change during apatite saturation. This suggests that degassing was not a major process during apatite crystallization (note that apatite is typically very late in the crystallization sequence of basaltic magmas). Based on the above

observations and conclusions, the primary eucrite magmatic δD is determined as -126 ±40 ‰.

*The δD of Vesta/HEDs.* While determining the δD of the material that accreted is difficult because of accretion processes, we are able to suggest the isotopic composition of a primary magma. To constrain what material contributed the volatile component to HEDs, one must be able to geochemically see through accretion processes, which were likely energetic and could have fractionated H isotopes with a preferential loss of [1]H. Thus we are able to give an upper limit of the material that accreted to form Vesta, -126 ±40 ‰. This value is within error of or close to the δD of carbonaceous chondrites, Earth, and the Moon [7]. If high-energy accretion processes fractionated H-isotopes, then this value could be *more negative*. The fact that bulk Vesta/eucrites is within error of carbonaceous chondrites could be fortuitous, although we could consider this unlikely. Instead, we suggest that the value presented here represents the source of volatiles for Vesta/the eucrite parent body(s).

[1]Papike, J.J., (1998), in *Reviews in Mineralogy: Planetary Materials*, J.J. Papike, Editor  [2] Goldoff, B., J.D. Webster, and D.E. Harlov, (2012) *Am.Min.* [3] McCubbin, F.M., et al. (2012) *Geology* **40**(8) [4]Sarafian, A.R., M.F. Roden, and A.E. Patiño Douce, (2013) *Meteoritics & Planet. Sci.* **48**(11) [5] Barrat, J.A. et al., (2011) *Geochim. Cosmochim. Acta* **75** [6] Villemant, B. and G. Boudon, (1999) *EPSL* **168**(3) [7] Saal, A.E. et al., (2013) *Science* **340**(6138)