The nature of volatiles in Vesta: Clues from apatite in eucrites. A. R. Sarafian*, M. F. Roden, A.E. Patiño-Douce, University of Georgia (povault@uga.edu*)

Introduction: The relative abundance and composition of volatiles is an important characteristic of planetary bodies, including the howardite-eucrite-diogenite (HED) parent body which is thought to be volatile-depleted [1]. Apatite, a volatile-bearing (F, Cl, OH) mineral, is a minor constituent of eucrites and can give insights into volatile composition of this parent body, inferred to be Vesta. We used apatite textures, mineral associations, and volatile compositions in eucrites in an attempt to characterize volatile reservoir(s) on Vesta. Basaltic eucrites (Stannern, Nuevo Laredo, Pasamonte, Juvinas, LEW 88010, LEW 88009, EET 87542, and GRA 98098) were selected for study to be representative of a large range in bulk rock Hf and Sc [2]. Four cumulate eucrites, Moore County, Serra de Magé, ALH 85001, and EET 87548 were also selected for study.

Methods: Following the procedures of Patiño-Douce et al. [3], we used the JEOL 8600 electron microprobe at the University of Georgia. The halogen hydroxyl-site was assumed to be filled by OH, F and Cl (i.e., $X_F + X_{Cl} + X_{OH} = 1$); OH was calculated by difference. The analytical totals were normalized to 25 oxygens (two formula units). Stoichiometry was used to define acceptable analyses based on occupancy of the P-site (P, Si, As), Ca-Site (Ca, Y, Ce, Sr, and Fe), and the halogen/hydroxyl site (F, Cl) such that: $5.8 <$ P-site < 6.1 cations, $9.7 <$ Ca-site < 10.1 cations, and halogen/hydroxyl site < 2.05 anions. To ensure the OH calculation was valid, we used the Cameca IMS-1280 ion probe at the Woods Hole Oceanographic Institute to measure OH directly. A Cs^+ primary beam was rastered (~30μm^2) and field apertures were used to collect from the center of the secondary ion beam (~15 μm^2) to reduce a crater edge effect. Negative ions ^{12}C, $^{16}O^1H$, ^{19}F, ^{31}P, ^{32}S, and ^{35}Cl were collected, and ^{31}P was used as a reference mass. A mass resolving power of 6872 was used, enough to separate ^{17}O from $^{16}O^1H$. Durango, Wilberforce, Eagle County, Mud Tank, and Ødergärden apatites were used as ion probe standards.

Results:

Apatite occurrence. Apatites in most meteorites reported on here (Stannern, Nuevo Laredo, Pasamonte, Serra de Magé, LEW 88010, LEW 88009, EET 87542, and ALH 85001 – no apatite was found in EET 87548) are subhedral, < 1 μm to 5 μm, and associated with ilmenite and troilite located in mesostasis.

In contrast, apatites in Moore County are euhedral, ~10 μm, and are contained within pyroxene and plagioclase. Apatites in Juvinas are anhedral, and found along cracks and grain boundaries. These veining apatites in Juvinas are ~3 μm wide and can reach ~1 mm in length.

Apatites in GRA 98098 and EET 90020 are heterogeneously distributed in the thin sections examined. Apatites in GRA 98098 (~40 μm) are in close proximity and in contact with a silica vein which is similar to hydrothermal quartz veins found in Serra de Magé [4]. Apatites in EET 90020 (15 μm to 1 mm) are quite abundant and are confined to a ~2 x 1.5mm area in the coarse-grained lithology described by Yamaguchi et al. [5].

Apatite composition. All the apatites are dominated by the fluorapatite component, however there are important and subtle differences in apatites from different eucrites. The apatites from most eucrites plot in the same area of an OH-F-Cl triangle (Fig. 1) although apatites from some eucrites have a relatively high OH content (Pasamonte, Juvinas, and Moore County) or a relatively high Cl content (GRA 98098). Apatite in GRA 98098 has 1 wt% Cl and 0.38 wt% H_2O (confirmed by ion probe) whereas most eucrites have ~0.15 wt% Cl.

Apatite from all eucrites are compositionally similar to apatites from terrestrial basaltic and gabbroic apatites [6]; however, apatites from eucrites generally occur with merrillite indicating a relatively water-poor magma [3]. Also, apatite from many eucrites are compositionally similar to mare basalt apatites. Apatite from GRA 98098 bears some compositional resemblance to KREEP apatite, but generally has more OH (Fig. 1).

Discussion:

Texture vs. composition. Apatites from most eucrites have relatively low OH, are fluorine-rich, and coexist with merrillite (Fig. 1). Because most apatite occurs in the mesostasis, apatite appears to be a late crystalizing phase in most cases [7], and because the apatites are relatively depleted in OH and Cl and rich in F, they crystallized from basalts that were degassed [8] or were intrinsically poor in Cl and water. If the former case is true, these apatites provide little information on the nature of the volatile component in primitive eucrite magmas.

However, several apatites show relatively unique textural/compositional features that may provide insight into primitive magmas or late stage fluids. Euhedral apatite contained in pyroxene and plagioclase in the Moore County eucrite crystallized relatively early in the crystallization history of the parent magma.

Thus, the volatile composition of this apatite may be indicative of the volatile composition of a relatively primitive eucrite magma (i.e., the least degassed). The relatively high OH content of Moore County apatites suggest that its parent magma had more water than the parent magmas of most eucrites studied but it also had very little Cl (Fig. 1). The lack of merrillite in this meteorite suggests that it may have crystallized from a more hydrous magma than the other meteorites [3].

Anhedral apatite in Juvinas is even more OH-rich than Moore County apatite (Fig. 1). The volatile composition and the occurrence of apatite in veins suggest that it crystallized from a late stage melt/fluid. This melt/fluid could be similar to melts/fluids involved in the Fe-metasomatism recognized by Barrat et al.[9]. Using partition coefficients from Mathez and Webster [10], we calculate that the melt/fluid that produced the apatites had significant water with F > Cl.

Although dominated by fluorapatite component, apatite in GRA 98098 is significantly more Cl-rich than any other apatite studied (Fig. 1). The unusual composition of the apatite is consistent with its occurrence in close proximity to a silica vein (possibly hydrothermal in origin [4]) and its volatile composition probably reflects that of a vein-forming fluid.

No merrillite was found in the apatite-rich region of the coarse-grained lithology in EET 90020 and the apatites are large and euhedral to subhedral. The coarse-grained lithology represents either melt produced during metamorphism [5] or the apatite-rich zones could reflect precipitation from a later fluid [11].

Model for volatiles on eucrite parent body. Based on their occurrence in mesostasis, many of the apatites studied here crystallized from residual melts that probably had degassed. Apatite included in pyroxene and plagioclase in Moore County suggests that there may have been some water in primitive melts on Vesta, but little Cl. Two types of veins are observed in the eucrites studied, silica veins with associated relatively Cl-rich apatite (in GRA 98098) and relatively OH-rich and Cl-poor apatite veins (in Juvinas). If the veins observed in eucrites are hydrothermal, then distinct types of hydrothermal fluids were active on Vesta.

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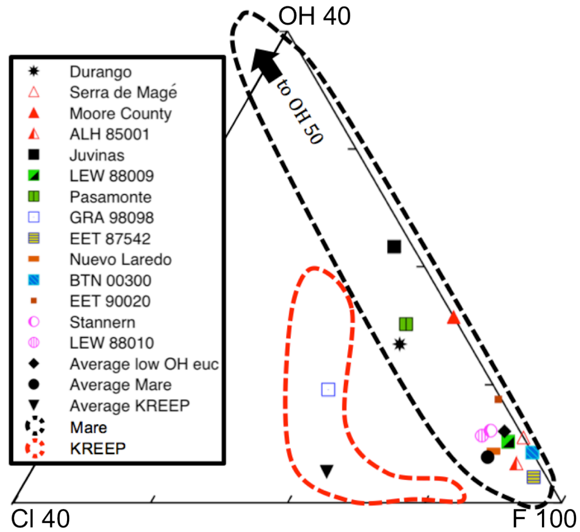

Figure 1. Truncated ternary diagram of apatite volatile contents. Durango is a secondary standard, Triangles are apatites from cumulate eucrites, boxes are apatites from main group eucrites, and pink circles are apatites from Stannern trend eucrites. Average low OH euc is an average of all apatite analyses from eucrites in black circle. Mare and KREEP apatite data from McCubbin et al. [12, 13].

References:

[1]Papike, J.J. (1997) *Reviews in Mineralogy,* 7-01-7-10. [2] Barrat, J., et al. (2007) *GCA*, 71, 4108-4124. [3]Patiño-Douce, A.E., et al. (2011) *Chemical Geology*, [4] Treiman, A.H. et al. (2004) *EPSL*, 219, 189-199. [5] Yamaguchi, A., et al. (2001) *GCA*, 65, 3577-3599. [6] Patiño-Douce, A.E. and M. Roden (2006) *GCA*, 70, 3173-3196 [7] McSween, H.Y., et al. (2010) *Space Sci. Reviews* 1-34 [8] Carroll, M.R. and J.D. Webster, (1994) *Reviews in Mineralogy* 231-279 [9]Barrat, J.A., et al., (2011) *GCA* 75, 3839-3852 [10] Mathez, E.A. and J.D. Webster (2005) *GCA*, 69 1275-1286. [11] Mittlefehldt, D.W. and M.M. Lindstrom (2003) *GCA*, 67, 1911-1934 [12] McCubbin, F.M., et al. (2010) *PNAS*, 107, 11223-11228 [13] McCubbin, F.M., et al. (2011) *GCA*, 75, 5073-5093