OXYGEN ISOTOPIC CONSTRAINTS ON THE NUMBER AND ORIGIN OF BASALTIC ACHONDRITE PARENT BODIES. Edward R. D. Scott[1], Richard C. Greenwood[2], Ian A. Franchi[2], Jean-Alix Barrat[3], and Ian S. Sanders[4], [1]HIGP, Univ. Hawaii, Honolulu, HI 96822, USA (escott@hawaii.edu), [2]PSSRI, Open University, Walton Hall, Milton Keynes MK7 6AA, UK, [3]CNRS UMR 6538 (Domaines Océaniques), U.B.O.-I.U.E.M., Place Nicolas Copernic, 29280 Plouzané Cedex, France, [4]Dept. of Geology, Trinity College, Dublin 2, Ireland.

Introduction: Two major studies of oxygen isotopes in HED meteorites, both using laser fluorination techniques, reached very different conclusions. Wiechert et al. [1] showed that nearly all of the 33 HED samples in their study had indistinguishable oxygen isotopic compositions. Three exceptions were Ibitira, Pasamonte, and Caldera, with Ibitira in particular showing a major deviation in Δ^{17}O from the measured mean HED value. Wiechert et al. [1] interpreted these results in terms of a single body for all eucrites with an isotopically heterogeneous outer layer, consistent with a partial melt origin. They inferred that partial melting was favored by the Mn-Cr and Hf-W isotopic data showing rapid formation in <5 Myr.

Analyses of 24 HED samples (excluding Ibitira) by Greenwood et al. [2] were consistent with those of Weichert et al. [1], but Greenwood et al. [2] disagreed about the extent of melting on the HED parent body. They argued that HEDs (like angrites) were derived from an isotopically homogenized magma ocean. The minor isotopic anomalies they observed in Pasamonte and the howardite, Bholgatti, were attributed to contamination of breccias by projectile material.

To help resolve this issue and to illuminate the origin and chronology of basaltic achondrites, we selected nine samples having anomalous oxygen isotopic compositions viz., Ibitira, Caldera, and Pasamonte, or unusual chemical compositions, textures, or ages suggesting they might be ungrouped basaltic achondrites like NWA 011 [3], viz., NWA 1240, Yamato 981651, Asuka 881394, EET90020, ALHA81001 and GRA98098. Ibitira is unique like NWA 011 because its Fe/Mn ratio in pyroxenes, alkali element concentrations, and Ti/Hf ratio are clearly outside the normal eucrite range [4]. Because Ibitira and NWA 011 are both unbrecciated, like the other major group of basaltic achondrites, the angrites, we selected unbrecciated eucrites (except for Pasamonte). Our studies were prompted by an investigation into the chronology and origin of basaltic meteorites [5] that highlighted the critical need for O isotope analyses of key meteorites.

Methods: Oxygen isotope analyses were performed by infrared laser-assisted fluorination following the procedures outlined by [6]. To assess the potential influence of weathering on two samples (NWA1240 and A881394) leaching experiments were undertaken using a solution of ethanolamine thioglycollate [7]. As a control, the Pasamonte fall was also leached using this method.

Results: Oxygen isotope results obtained in this study are plotted on Fig. 1. Analyses of Caldera, Y981651, ALHA81001, EET90020, and GRA98098 plot on or close to the eucrite fractionation line (EFL) of [2] and can therefore be considered to represent normal eucrites. Pasamonte and NWA 1240 both plot off the EFL while Ibitira and Asuka 881394 are very significantly displaced from it.

Ibitira: Our analyses, which are consistent with those of [1], plus the unique chemical and physical properties of Ibitira [4] show that it is not from the HED source. Given the degree of impact mixing among HED breccias, the surface and upper mantle of Vesta must be well sampled so that Ibitira is almost certainly from another asteroid. Since Ibitira falls on the angrite mass fractionation line, both could come from the same source. Angritic and eucritic melts can both be produced from an Allende-like starting composition by changing the oxygen fugacity [8], however, a common source seems improbable.

Asuka 881394: A881394, which has been identified as an exceptional rock on the basis of its mineralogy, isotopic composition, and great antiquity [9-11], has an oxygen isotopic composition clearly unlike those of the HEDs (Fig 1). Like Ibitira it is deficient in Na and K relative to eucrites [12], but unlike Ibitira it plots off the Mn-Cr whole-rock HED isochron [10]. Even though its Mn/Cr ratio of 34 [12] is typical of eucrites, A881394 clearly comes from a separate source. The oxygen isotope analysis of A881394 is also distinct from that of Ibitira and hence both are unlikely to share the same asteroidal source. Leaching experiments performed on A881394 show no significant shift in Δ^{17}O indicating that terrestrial weathering has not altered the samples isotopic composition. However, replicate analyses showed somewhat more scatter than normal, suggesting some possible isotopic heterogeneity due to persistant weathering products.

Pasamonte: Our data for a dark clast and matrix sample are indistinguishable from previously published Pasamonte data [1, 2] and new whole rock analyses (Fig. 1). All Pasamonte analyses lie significantly above the HED range (Fig. 1). Consistent with its status as a fall, leaching of Pasamonte showed no discernable isotopic shift (Fig. 1).

Contamination by an ordinary chondrite projectile could produce an offset in Δ^{17}O like that observed. However, there is no evidence for chondritic material in this meteorite with the possible exception of a single H or CI contaminated clast [13], and OC clasts are absent in other HEDs. Similarly, the uniform oxygen isotopic compositions of clast and matrix samples from this meteorite also argue against random mixing of projectile contamination. Given the isotopic homogeneity of eucrites and diogenites, we infer that Pasamonte, although considered a typical unequilibrated eucrite, is not derived from the HED body. Chromites in Pasamonte are richer in Al and lower in Ti than in eucrites [14] supporting a separate source.

NWA 1240: NWA 1240 was inferred to be an impact-melted cumulate eucrite to account for its positive Eu anomaly, low concentrations of incompatible elements, and fine-grained texture [15]. Fig. 1 shows that NWA 1240 has an oxygen signature distinct from normal eucrites with a much lower $\delta^{18}O$ value, and a $\Delta^{17}O$ value significantly below the EFL [2]. Leaching of NWA 1240 had little impact indicating that the sample is essentially unweathered. Contamination by ~1% of C chondrites, which accounts for the low $\Delta^{17}O$ value of Bholghati [2], is excluded for NWA 1240 by its low siderophile concentration; 5 ppm Ni [15] cf. ≈500 ppm for howardites [16]. Major contamination by an achondritic projectile like NWA 011 could in theory explain the O anomaly in NWA 1240. However, the most credible explanation is that NWA 1240 is not an impact melt and comes from a separate parent body. This would also help to account for its unusually high Mg and Cr and relatively low Na and Ca [15].

Bermingham et al. [17] identified four unbrecciated non-cumulate eucrites with positive Eu anomalies suggesting a possible link with NWA 1240. However, one of these, EET90020, lies on the EFL line (Fig. 1), and is clearly unrelated to NWA 1240.

Four of the basalts that we have analyzed (EET90020, GRA98098, Caldera and Ibitira) belong to the group of cumulate eucrites and unbrecciated non-cumulate basalts with 4.47-4.50 Gyr Ar-Ar ages that Bogard and Garrison [18] thought were excavated in a single large impact on Vesta. However, two impacts are required as Ibitira was not present on Vesta. Nevertheless, early removal from Vesta or a Vesta-like body may be a key feature for many unbrecciated and unshocked asteroidal basalts including angrites [19].

Conclusions: We infer that HED meteorites come from an isotopically homogenized source consistent with a magma ocean on Vesta. Ibitira, Asuka 881394, Pasamonte, and NWA 1240 appear to be derived from four additional bodies. Given the abundance of ungrouped irons and newly discovered basaltic asteroids lying outside the Vesta family [21], we should not be surprised to find basaltic meteorites that are derived from six different bodies. Are there more?

Caldera, Y981651, ALHA81001, EET90020, and GRA98098 have HED-like oxygen isotopes. However, the abundance of differentiated bodies in the Vesta region of O isotopic space means we cannot exclude a separate source. Y981651 with its unusual composition and vesicles [20] deserves further study. Note that no single parameter can be used to classify all asteroidal basalts, though oxygen isotopes are clearly invaluable. Like Mittlefehldt [4], we suggest that the term "eucrite" should be reserved for basaltic meteorites plotting on the diogenite-eucrite O isotopic line.

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Figure 1. Basaltic meteorites analyzed in this study (squares) compared to data of [2] (solid symbols). Horizontal lines are mass fractionation lines for Earth (TFL), angrites (AFL), eucrites and diogenites (EFL), and main-group pallasites [2, sci]. Also shown are the results of deweathering experiments (red squares). P1=Pasamonte matrix, P2=Pasamonte average, P3=Pasamonte dark clast.