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Edward R.D. Scott, Richard C. Greenwood, Ian A. Franchi, Ian S. Sanders

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OXYGEN ISOTOPIC CONSTRAINTS ON THE ORIGIN AND PARENT BODIES OF EUCRITES, DIOGENITES, AND HOWARDITES

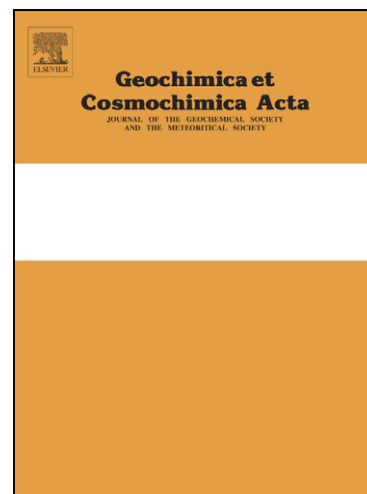Edward R. D. Scott[1], Richard C. Greenwood[2], Ian A. Franchi[2], and Ian S. Sanders[3]

[1]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, HI 96822, USA (escott@hawaii.edu)

[2]PSSRI, Open University, Walton Hall, Milton Keynes MK7 6AA, UK

[3]Department of Geology, Trinity College, Dublin 2, Ireland

A few eucrites have anomalous oxygen isotopic compositions. To help understand their origin and identify additional samples, we have analyzed the oxygen isotopic compositions of 18 eucrites and four diogenites. Except for five eucrites, these meteorites have $\Delta^{17}O$ values that lie within 2σ of their mean value viz., -0.242±0.016‰, consistent with igneous isotopic homogenization of Vesta. The five exceptional eucrites—NWA 1240, Pasamonte (both clast and matrix samples), PCA 91007, A-881394, and Ibitira—have $\Delta^{17}O$ values that lie respectively 4σ, 5σ, 5σ, 15σ, and 21σ away from this mean value. NWA 1240 has a $\delta^{18}O$ value that is 5σ below the mean eucrite value. Four of the five outliers are unbrecciated and unshocked basaltic eucrites, like NWA 011, the first eucrite found to have an anomalous oxygen isotopic composition. The fifth outlier, Pasamonte, is composed almost entirely of unequilibrated basaltic clasts. Published chemical data for the six eucrites with anomalous oxygen isotopic compositions (including NWA 011) exclude contamination by chondritic projectiles as a source of the oxygen anomalies. Only NWA 011 has an anomalous Fe/Mn ratio, but several anomalous eucrites have exceptional Na, Ti, or Cr concentrations. We infer that the six anomalous eucrites are probably derived from five distinct Vesta-like parent bodies (Pasamonte and PCA 91007 could come from one body). These anomalous eucrites, like many unbrecciated eucrites from Vesta, are probably deficient in brecciation and shock effects because they were sequestered in small asteroids (~10 km diameter) during the Late Heavy Bombardment following ejection from Vesta-like bodies. The preservation of Vesta's crust and the lack of deeply buried samples from the hypothesized Vesta-like bodies are consistent with the removal of these bodies from the asteroid belt by gravitational perturbations from planets and protoplanets, rather than by collisonal grinding.

1. INTRODUCTION

Oxygen isotopic compositions of igneous meteorites provide powerful constraints on their genetic relationships and origins. The largest group of these meteorites, the howardites, eucrites, and diogenites, commonly called HED meteorites, have a restricted range of oxygen isotope compositions that distinguishes them from other achondrites and rocks from Earth, Mars and the Moon (Clayton and Mayeda, 1996; Mittlefehldt et al., 1998). The HED meteorites fall into four main groups. Basaltic (or non-cumulate) eucrites are basalts that formed originally in extrusive flows or minor intrusions but are now mostly metamorphosed and brecciated. Cumulate eucrites are coarse-grained gabbros, which are thought to have formed in shallow magma chambers below the basaltic eucrites, and are mostly unbrecciated (Takeda, 1997). Diogenites are orthopyroxenites, which were probably cumulates from the same or deeper magma chambers, and are now mostly monomict breccias. Howardites are fragmental breccias composed of eucrite and diogenite material that are derived from the regolith or mega-regolith of the HED parent body (Keil, 2002). There is no consensus on the igneous processes that generated eucrites and diogenites (Mittlefehldt, 2007), but cooling of a magma ocean appears to provide a more comprehensive explanation for the diverse lithologies than partial melting (Righter and Drake, 1997; Ruzicka et al., 1997). Spectrometric studies of meteorites and asteroids strongly suggest that HEDs are derived from Vesta, the third largest asteroid, and its family of sub-10 km diameter asteroids (Drake, 2001; Pieters et al., 2005).

NWA 011 is mineralogically very similar to the basaltic eucrites but has a very different oxygen isotopic composition and contains pyroxenes with significantly higher Fe/Mn ratios (~65 cf. 30-40 in eucrites) showing that it probably comes from a separate parent body (Yamaguchi et al., 2002; Floss et al., 2005). Although Vesta appears to be the only intact basaltic asteroid (Pieters et al., 2005), there are many smaller asteroids (≤30 km across) with reflectance spectra like those of Vesta (called V-types) that have orbits outside Vesta's family (e.g., Lazzaro et al., 2000; Moskovitz et al., 2008). One of the V-type asteroids that lies beyond the 3:1 resonance marking the outer edge of the Vesta family, such as 1459 Magnya, may have been the source of NWA 011.

Two groups, Wiechert et al. (2004) and Greenwood et al. (2005), have used infrared laser-assisted fluorination to analyze the oxygen isotopic compositions of the HED achondrites to much higher precision than had been achieved by Clayton and Mayeda (1996) using the externally heated Ni-rod bomb technique. Both groups agreed that most HEDs have indistinguishable $\Delta^{17}O$ values (see section 3 for a definition of this term), consistent with an origin from a single homogeneous source, and that some howardites have significantly lower $\Delta^{17}O$ values because of contamination by a few vol. % of CM and CR carbonaceous chondrite projectiles (Zolensky et al., 1996; Fig. 1). However, the two groups differed in their interpretation of the data for the few eucrites that were found to have aberrant oxygen isotopic compositions.

Wiechert et al. (2004), who analyzed 26 eucrites and diogenites, concluded that four of the eucrites, Ibitira, Pasamonte, Caldera and ALHA78132, had significantly higher $\Delta^{17}O$ values, which deviated by 13σ, 3σ, 2.5σ and 2σ, respectively from the mean value for the other eucrites and diogenites. From this they inferred that Vesta retained some primary isotopic heterogeneity,

consistent with the formation of the basaltic eucrites by partial melting. However, they noted, that an origin for Ibitira on a separate parent body could not be excluded. Such an origin was subsequently favored by Mittlefehldt (2005), who identified additional unique chemical and mineralogical features of Ibitira.

Greenwood et al. (2005), who analyzed 18 eucrites and diogenites, found only one sample, Pasamonte, with an aberrant oxygen isotopic composition. (They did not analyze Ibitira, Caldera, and ALHA78132.) Contrary to Wiechert et al. (2004), they attributed Pasamonte's anomalous oxygen isotopic composition to contamination by an ordinary or CI carbonaceous chondrite projectile. More importantly, they inferred from the homogeneity of the 17 other meteorites that Vesta had been isotopically homogenized and had therefore probably melted to form a magma ocean, favoring an origin for eucrites and diogenites as residual liquids and cumulates. Greenwood et al. (2005) also showed for the first time that the oxygen isotopic compositions of the eucrites could be clearly resolved from those of the other major group of asteroidal basalts, the angrites. Clayton and Mayeda (1996) had previously concluded that the two groups had virtually indistinguishable oxygen isotopic compositions.

This study was stimulated by efforts to understand the chronology of basaltic meteorites (Sanders and Scott, 2007a,b), and by the discovery of eucrites with anomalous chemical and mineralogical properties and radiometric ages (e.g., Nyquist et al., 2003b) which led us to speculate that additional eucrites may have aberrant oxygen isotopic compositions. Our goals were to reanalyze oxygen isotopes in the anomalous eucrites identified by Wiechert et al. (2004) and Greenwood et al. (2005), to search for other eucrites or diogenites with aberrant oxygen isotopic compositions, and to clarify the origin of these anomalous meteorites. They could represent parts of Vesta that were not homogenized during melting, or regions where projectiles contaminated Vesta's surface, or they might be derived from different parent bodies altogether. Other possible causes for discrepant $\Delta^{17}O$ values are geological processes that generate mass-independent isotope fractionation effects (Thiemens, 2006), and mass-dependent fractionation processes with slightly different slope factors (Rumble et al., 2007). In addition, terrestrial weathering may cause significant shifts in the oxygen isotopic composition of meteorite finds (Greenwood et al., 2008a).

2. SAMPLES ANALYZED AND TERMINOLGY

We analyzed 18 eucrites (basaltic, cumulate, and polymict) and four diogenites, which are listed with their classifications in Table 1. These include three of the four eucrites identified by Wiechert et al. (2004) as having anomalous oxygen isotopic compositions: Ibitira, Pasamonte, and Caldera. The fourth, ALHA78132, was not analyzed as it is probably paired with ALHA76005 (see Scott, 1989) and the mean $\Delta^{17}O$ value obtained by Wiechert et al. (2004) for these paired samples closely matches their mean eucrite-diogenite value (Fig. 1). To test whether the Pasamonte samples could have been contaminated by projectile material, we analyzed a 2 mm black clast excavated from the friable matrix of lighter colored fragments. This clast appeared to be typical of rare fine-grained clasts laden with very finely dispersed opaque grains. Other eucrites were selected because they showed some of the characteristic features of Ibitira, NWA 011, or Pasamonte, viz., unbrecciated like NWA 011 and Ibitira, vesicles as in Ibitira,

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unequilibrated pyroxenes with diverse Mg/Fe ratios as in Pasamonte, or because they have other exceptional compositional, textural or isotopic characteristics or unusual Ar-Ar ages (Table 1).

Three unmetamorphosed eucrites were selected for comparison with Pasamonte, which is classed as a type 2 on the Takeda-Graham (1991) type 1-6 scale of metamorphic equilibration: two are type 2-3 unbrecciated basaltic eucrites, NWA 1000 and Y-981651 (Warren, 2002; 2003), and the third, Y-82202, is a monomict breccia composed of clasts with pyroxenes that show Pasamonte-like zoning and textures overlain by a network impact-melted glass veins (Yamaguchi and Takeda, 1992; Buchanan et al., 2005). In addition we analyzed four polymict eucrites that contain unequilibrated clasts with subophitic textures and pyroxene compositions like those in Pasamonte: Yamato 75011 (Takeda and Graham, 1991; Warren and Kallemeyn, 2001), the possibly paired samples Y-74159 and Y-74450 (Takeda et al., 1983), and Y-790260 (Antarctic Meteorite Data Base; see http://metdb.nipr.ac.jp/am_db_public).

Although diogenites with anomalous oxygen isotopic compositions have yet to be identified, we selected four diogenites with unusual properties as possible candidates. GRA 98108 is one of the few unbrecciated diogenites, though it is moderately shocked, and also contains ~30% olivine, cf. 0-3% in most diogenites (McCoy, 2000; Righter, 2001). GRO 95555 is classified as an anomalous diogenite because it is unbrecciated, unshocked, and granular in texture (Papike et al., 2000). NWA 1461 is the most magnesian diogenite known and has a coarse-grained, partly cataclastic texture (Bunch et al., 2007). The fourth diogenite is Y-75032, a so-called Yamato Type B diogenite, which is composed of heavily shocked clasts with especially Fe-rich pyroxene in a glassy impact melt matrix (Takeda and Mori, 1985). In terms of major and minor elements it is intermediate in composition between diogenites and cumulate eucrites and appears to be an impact-melted mixture. However, trace elements suggest that it is one of only a few diogenites that do not form an apparent igneous sequence (Mittlefehldt, 1994).

The classifications in Table 1 are based largely on those in the Meteoritical Bulletin Database (see http://tin.er.usgs.gov/meteor/metbull.php). However, many HED meteorites are complex mixtures of different rock types and these have not been classified in a consistent fashion. For example, the Database lists 8 types of eucrites. According to the Database definition, monomict eucrites are breccias that are composed of a single type of eucrite. However, some authors include unbrecciated non-cumulate eucrites in the monomict eucrite group. By "unbrecciated" we mean a rock that is not a fragmental or impact melt breccia. Eucrites with recrystallized textures like Ibitira and EET 90020 are called unbrecciated, even though they may have been brecciated before recrystallization (e.g., Yamaguchi et al., 2001).

An unresolved issue is what to call rocks with the major element composition and mineralogy of eucrites but anomalous oxygen isotopic compositions, such as NWA 011, that do not appear to be derived from the HED parent body. Can they be called ungrouped eucrites, or are eucrites, by definition, derived only from the HED parent body? Here we adopt a broad definition of "eucrite" that does not require the source body to be identified, and return to this question in the final section. Note that the original eucrites were meteorites named by Rose in 1863 (e.g., Greshake, 2006), not terrestrial rocks as commonly believed (e.g., Marvin, 2006).

3. METHODS

Oxygen isotope analyses were carried out using an infrared laser-assisted fluorination system (Miller et al., 1999). For most samples analyzed in this study, 50-150 mg interior chips were crushed and homogenized, with replicate analyses undertaken on ~2 mg aliquots of these powders. To maximize yields and decrease the risk of cross-contamination the powdered samples were fused in vacuum to form a glass bead prior to fluorination. O_2 was liberated by heating the glass beads using an infrared CO_2 laser (10.6 μm) in the presence of 210 torr of BrF_5. After fluorination, the O_2 released was purified by passing it through two cryogenic nitrogen traps and over a bed of heated KBr. O_2 was analyzed using a Micromass Prism III dual inlet mass spectrometer. All oxygen isotope measurements were made at the Open University using a pure O_2 working reference gas that was directly calibrated against the reference standard, Vienna Standard Mean Ocean Water (VSMOW), at the Hebrew University of Jerusalem using the procedures described by Barkan and Luz (2005). Oxygen isotopic analyses are reported in standard δ notation where $\delta^{18}O$ has been calculated as: $\delta^{18}O = [(^{18}O/^{16}O_{sample}/^{18}O/^{16}O_{ref})-1] \times 1000$ per mil (‰) and similarly for $\delta^{17}O$ using the $^{17}O/^{16}O$ ratio. $\Delta^{17}O$, which represents the deviation from the terrestrial fractionation line, has been calculated using the linearized format of Miller (2002):

$$\Delta^{17}O = 1000\ln(1+ \delta^{17}O/1000) - \lambda\ 1000\ln(1+ \delta^{18}O/1000)$$

where $\lambda = 0.5247$. (Note that some authors omit the factors of 1000 in both definitions.) Published system precision (1σ) based on replicate analyses of international (NBS-28 quartz, UWG-2 garnet) and internal standards, is approximately ±0.04‰ for $\delta^{17}O$; ±0.08‰ for $\delta^{18}O$; ±0.02‰ for $\Delta^{17}O$ (Miller et al., 1999). Replicate analyses of the international UWG-2 garnet standard measured during the course of this study gave somewhat smaller values for the 1σ precision: ±0.03‰ for $\delta^{17}O$; ±0.07‰ for $\delta^{18}O$; ±0.01‰ for $\Delta^{17}O$. The quoted precision (1σ) for the meteorite samples is based on 2 or more replicate analyses. In cases where two replicates showed relatively poor agreement or their mean value appeared anomalous, one or more additional analyses were performed.

To check whether any of the anomalous $\Delta^{17}O$ values seen in meteorite finds could result from terrestrial weathering, we conducted a series of leaching experiments using 6M HCl or ethanolamine thioglycolate (EATG) (Cornish and Doyle, 1984), or both. A recent evaluation study by Greenwood et al. (2008a) suggests that both methods are effective at removing the bulk of the terrestrial weathering products in hot and cold desert finds.

4. RESULTS

Our oxygen isotope data for 18 eucrites and 4 diogenites are given in Table 2 and plotted in Fig. 2. (Individual analyses are presented in Electronic Annex Table EA1.) Figure 2 shows clearly that there are five samples, Ibitira, A-881394, PCA 91007, Pasamonte, and NWA 1240 that lie well outside the field defined by the remainder. To test whether A-881394, PCA 91007, and NWA 1240 have aberrant oxygen isotopic compositions because of terrestrial weathering, we conducted leaching experiments on these finds, as well as two NWA samples, and as a control, the meteorite fall, Pasamonte. The results of these experiments are shown in Fig. 3. For all the meteorite finds investigated except NWA 1000, the shifts between the oxygen isotopic

compositions of the acid leached samples and the corresponding untreated samples were not significant. The $\Delta^{17}O$ shifts were <0.025‰ and the $\delta^{18}O$ shifts were under 0.15‰, except for NWA 1000, which shifted 0.19‰. This eucrite contains carbonate veins and is therefore likely to have suffered significant alteration (Meteoritical Bulletin Database; see http://tin.er.usgs.gov/meteor/metbull.php), thus it is probable that even the acid treatment has not completely eliminated the effects of terrestrial oxygen isotope contamination. As the $\Delta^{17}O$ of the untreated NWA 1000 sample is at the high end of the eucrite range, we infer that the $\Delta^{17}O$ of the acid leached sample is a better indication of this sample's primary composition. The results of these leaching experiments indicate that the anomalous isotopic compositions of A-881394, PCA 91007, and NWA 1240 are a primary feature and are not the result of terrestrial weathering processes.

The close proximity of the $\delta^{18}O$ values of the abnormal eucrite, NWA 1240, and the four diogenites in Fig. 2 suggests the possibility that the abnormal $\delta^{18}O$ value of NWA 1240 might reflect an atypically high proportion of pyroxene in our analyzed sample. To test this possibility we separated grains of pyroxene, both clear and translucent, from fresh samples of NWA 1240 leaving residual matrix samples that we infer are correspondingly plagioclase-rich. Mean analyses of four replicates of each of the four samples are listed in Table 2 and shown in Fig. 4. The two pyroxene samples have significantly lower $\delta^{18}O$ values than the two matrix samples, consistent with the offset between normal eucrites and diogenites. In addition, all four phase separates of NWA 1240 have lower $\delta^{18}O$ values than the diogenites. Thus the anomalously low $\delta^{18}O$ value of NWA 1240 cannot be attributed to an abnormally high proportion of pyroxene. The analyses of the NWA 1240 phase separates also confirm the abnormally low $\Delta^{17}O$ values that were obtained for the bulk samples. The mean $\Delta^{17}O$ value of the phase separates of -0.269±0.013‰ (1σ) is close to that of the 7 bulk analyses of -0.272±0.009‰ (1σ). Only the translucent pyroxene sample has a $\Delta^{17}O$ value (-0.250‰) inside the range observed for the normal eucrites and diogenites (-0.255 to -0.226‰). Since the phase separates were not leached in acids, both the translucency and the smaller $\Delta^{17}O$ value of this pyroxene sample may reflect weathering.

All four diogenites and 13 of the eucrites have $\Delta^{17}O$ values lying within 2σ (±0.016‰) of their mean value of -0.242‰. The five abnormal eucrites have $\Delta^{17}O$ values that lie >4σ from this mean $\Delta^{17}O$ value: NWA 1240 plots 4σ below the mean, Pasamonte and PCA 91007 are 5σ above, and A-881394 and Ibitira lie respectively 15σ and 21σ above the mean value (Fig. 5). One of these five eucrites, NWA 1240, also has a $\delta^{18}O$ value that differs significantly from that of the normal eucrites, lying 5σ below the mean value of normal eucrites. The $\delta^{18}O$ values for A-881394 and Ibitira are nearly 2σ above the mean value of normal eucrites.

The four analyzed diogenites have $\Delta^{17}O$ values that are indistinguishable from those of the normal eucrites, but as noted by Greenwood et al. (2005), the $\delta^{18}O$ values of diogenites are lower than those of the normal eucrites (by 0.3-0.4‰), consistent with their much lower plagioclase contents and high-temperature plagioclase-pyroxene equilibration (Clayton, 1993). With the exception of NWA 1000, which was discussed above, the normal eucrites in Table 2 show a narrow range of $\delta^{18}O$ values: 3.68±0.12‰ (1σ).

To provide some estimate of the expected spread of $\Delta^{17}O$ values assuming that the HED body is isotopically homogeneous, we made 11 analyses over a 3 day period of the terrestrial garnet standard UWG-2. The $\Delta^{17}O$ values of these analyses have a mean and standard deviation of -0.007±0.010‰. This standard deviation is similar to those of 13 Pasamonte replicate analyses measured over a 4 year period, 0.008‰. For comparison, the mean and standard deviation of all 40 individual analyses over a period of 14 months of the 17 normal eucrites and diogenites (excluding the 5 eucrites with abnormal $\Delta^{17}O$ values) is -0.242±0.013‰. This scatter is only ~25% larger than we obtained for the 11 analyses of the UWG-2 standard over 3 days and could be due entirely to weathering of meteorites and experimental errors. We infer that the 17 normal eucrites and the 4 diogenites could have been derived from an isotopically homogenized source.

4.1. Comparison with published data

To compare our eucrite and diogenite oxygen isotopic data with published data, we first exclude the small number of outliers with $\Delta^{17}O$ values >3σ from the mean. Table 3 and Fig. 5 show that our mean $\Delta^{17}O$ value for normal eucrites and diogenites, 0.242±0.004‰, is very close to that of Greenwood et al. (2005), -0.239±0.003‰. The uncertainties quoted here are twice the standard error of the mean (SEM) and are comparable, even though Greenwood's samples were all falls and ours, except for Ibitira and Pasamonte, are finds. Note that the 2σ standard deviation of our $\Delta^{17}O$ values for eucrites and diogenites excluding outliers (0.016‰) is ~10× smaller than the comparable value of Clayton and Mayeda (1996). The mean $\Delta^{17}O$ value for 13 HEDs excluding Pasamonte reported by Ziegler and Young (2007), 0.238±0.031‰ (1σ), is close to ours, but their standard deviation is much larger.

The precision of the analyses by Wiechert et al. (2004) is quite comparable to ours, but our mean $\Delta^{17}O$ value for eucrites and diogenites, -0.242±0.004‰ (2× SEM), is significantly different from that of Wiechert et al., -0.218±0.004‰ (2× SEM). Since 16 of the 29 eucrites and diogenites analyzed by Wiechert et al. (2004) were not analyzed at the Open University and many are falls, the discrepancy might be attributed to sample selection or weathering of finds. However, Table 3 shows that the difference between the mean $\Delta^{17}O$ values for 9 falls analyzed by both Wiechert et al. and Greenwood et al., 0.021±0.007‰ (2× SEM), is the same as the difference for all analyzed eucrites and diogenites, 0.021±0.006‰ (2× SEM). In addition, Fig. 1 shows that the falls and finds analyzed by Wiechert et al. (2004) do not differ significantly in their means or ranges of $\Delta^{17}O$ values. Thus sample selection and weathering of finds are not responsible for the difference.

Although Wiechert et al. (2004) used the same linearized form of the definition for $\Delta^{17}O$ that was adopted in the other two studies (Miller, 2002), Wiechert et al. used a different slope factor λ — 0.5305 rather than the value of 0.5247 recommended by Miller (2002) and used by Greenwood et al. (2005) and this study. However, use of the same slope factor causes the difference between the mean $\Delta^{17}O$ values for eucrites and diogenites to double in size to ~0.04‰. The most likely explanation for the discrepancy between the Open University and Wiechert et al. data is that it reflects differences in the procedures that were used to relate the working standard oxygen gas for the mass spectrometer with the internationally accepted reference material: Vienna Standard Mean Ocean Water (VSMOW). Current procedures used by the two labs for determinations of $\Delta^{17}O$ values appear to be well aligned (Rumble et al., 2007). We infer that the mean $\Delta^{17}O$ value and normal range for eucrites and diogenites should not be determined by simply combining data

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from Wiechert et al. (2004) and Greenwood et al. (2005). It is also clear that caution should be exercised when using data from different investigators when differences of the order of 0.03% or less in $\Delta^{17}O$ are critical, as in this study.

In Table 3, we also compare data for Caldera, Ibitira, and Pasamonte. With one exception, our data agree well, after allowance for the systematic Wiechert-Greenwood offset. In the case of Caldera, our $\Delta^{17}O$ value is very consistent with the eucrite-diogenite mean, unlike that of Wiechert who found a 2.5σ departure from the mean. We infer that the latter result, which came from a single analysis, was affected by weathering or was a statistical anomaly. (Caldera has a unique brown color due to weathering.) The results for Ibitira and Pasamonte are discussed in detail below.

5. DISCUSSION

5.1. Eucrites with anomalous oxygen isotopic compositions

In this section we review the chemical, mineralogical and isotopic properties of the six eucrites with anomalous oxygen isotopic compositions, i.e., the five that were analyzed in this study plus NWA 011, to clarify whether they could be derived from contaminated impact melts, an isotopically heterogeneous parent body, or whether they might be derived from separate bodies.

5.1.1. Asuka 881394
Asuka 881394 is clearly an exceptional achondrite on the basis of its mineralogy, chemical, and isotopic composition and great antiquity (Takeda et al., 1997; Nyquist et al., 2003b). Our data show very clearly that its oxygen isotopic composition is quite distinct from those of normal eucrites, Ibitira, and other grouped and ungrouped achondrites. Although its bulk Fe/Mn ratio of 34 is typical for eucrites, A-881394 has extremely low concentrations of Na and K—lower than in all other eucrites and closer to angrites—and an exceptionally low Ga/Al ratio (Warren et al., 1996a,b). Siderophile abundances in A-881394 are comparable to those in eucrites (Warren, 1999) precluding an explanation for the oxygen isotope anomaly involving contamination by an ordinary chondrite projectile. A-881394 has Mg-rich pyroxenes and low concentrations of incompatible elements like cumulate eucrites but it has a unique granulitic texture (Fig. 6a). In addition its plagioclase is even more calcic than in cumulate eucrites, An_{98} cf. An_{91-95} and An_{75-93} in cumulate and non-cumulate eucrites, respectively (Nyquist et al., 2003b; Mittlefehldt, 2007).

If the Pb-Pb age of 4566.5±0.3 Myr of A-881394 dates crystallization as Amelin et al., (2006) infer, it cannot have formed in the environment of the HED achondrites, which crystallized no earlier than their whole rock Al-Mg, Hf-W, and Mn-Cr ages of 4562-3 Myr (e.g., Sanders and Scott, 2007b). However, the ^{53}Mn-^{53}Cr and ^{26}Al-^{26}Mg ages of A-881394 (Wadhwa et al., 2005) are 2-3 Myr younger than its ^{207}Pb-^{206}Pb age, which raises some concerns about the validity of the latter (Sanders and Scott, 2007a). Even though its oxygen isotope composition appeared at that time to be typically eucritic, Wadhwa et al. (2005) suggested that Asuka 881394 may have originated on another parent body as its bulk composition clearly lies above the eucrite-diogenite whole rock isochron on the $^{53}Cr/^{52}Cr$ vs. $^{55}Mn/^{52}Cr$ diagram. Although some eucrites lie off the isochron (e.g., Nyquist et al., 1997; Yamuguchi et al., 2001), the great antiquity of the A-881394 suggests its deviation from the isochron requires a very different source region from the eucrites

and diogenites. [The eucrite, Bunburra Rockhole, has an oxygen isotopic composition suggesting it may be derived from the same body as A-881394 (Bland et al., 2009).]

5.1.2. Ibitira

Ibitira has long been considered an archetypal eucrite, and until Caldera was found (Boctor et al., 1994), it was considered to be the only known unbrecciated non-cumulate eucrite (Fig. 6b). Prompted by the discovery of its highly aberrant oxygen isotope composition by Wiechert et al. (2004), Mittlefehldt (2005) identified many other distinctive or unique mineralogical and chemical features of Ibitira and concluded that it formed on a separate body. The Fe/Mn ratio in Ibitira's pyroxenes of 36 is above the range of 31-33 commonly found in eucrites (Mittlefehldt, 2005), although Mayne et al. (2009) report some compositional overlap. Lentz et al. (2007) also note that Bouvante, which has normal eucrite oxygen isotopic composition (Wiechert et al., 2004), has a pyroxene Fe/Mn ratio of 40 (Mittlefehldt et al., 1998). Pyroxenes in Ibitira have a lower Fe/Mg ratio (1.42±0.03) than those of other basaltic eucrites (1.57-1.73), according to Mittlefehldt (2005). Ibitira has an anomalously low concentration of alkali elements. Its Na/Ca ratio is $0.035 \times$ CI chondrites cf. 0.07-0.10 in normal eucrites and this is reflected in its plagioclase composition of An_{95} cf. An_{75-93} in normal basaltic eucrites (Mittlefehldt et al., 1998). However, Ibitira's plagioclase composition is matched by that of ALHA81001 (Mayne et al., 2009), which has a normal oxygen isotopic composition (Table 2). Titanium is enriched in Ibitira relative to other refractory lithophiles, e.g., Ti/Hf is above the basaltic eucrite range (Mittlefehldt, 2005). However, Ibitira plots nicely on the eucrite-diogenite whole rock isochron on the $^{53}Cr/^{52}Cr$ vs. $^{55}Mn/^{52}Cr$ diagram (Lugmair and Shukolukov, 1998).

Gomes and Keil (1980) suggested that the presence of vesicles and low volatile content of Ibitira could be accounted for by an origin in a superheated impact melt. Contamination by an impactor might also account for the unusual oxygen isotope composition. However as Mittlefehldt (2005) noted, a chondritic projectile would leave enhanced siderophiles, which are not found in Ibitira. An achondritic projectile cannot be excluded but the simplest explanation is that Ibitira comes from a separate differentiated asteroid.

Our oxygen isotopic data for Ibitira, which are indistinguishable from those of Wiechert et al. (2004) after allowance for the systematic offset between data sets (Table 3), show that Ibitira's $\Delta^{17}O$ value is indistinguishable from those of the angrites (Fig. 2), suggesting that they might come from the same body. Ibitira and the angrites are both more depleted in Na and K than the basaltic eucrites (Warren et al., 1996b) and eucrite-like and angrite-like partial melts can be produced from a single source by changing the oxygen fugacity (Jurewicz et al., 1993). However, we lack breccias containing both types of basalt and it is more plausible that they come from separate bodies. The coincidence of $\Delta^{17}O$ values for lithologies that come from distinct parent bodies is not unreasonable, as can clearly be demonstrated for terrestrial rocks, aubrites and enstatite chondrites (Newton et al., 2000). [The achondrite, NWA 2824, has an oxygen isotopic composition like that of Ibitira suggesting that it may come from the same parent body (Bunch et al., 2009).]

5.1.3. NWA 011

Although the mineralogy and major element composition of NWA 011 resemble those of the non-cumulate eucrites, Yamaguchi et al. (2002) and Floss et al. (2005) inferred from its unique oxygen isotopic composition ($\Delta^{17}O$ is -1.6‰ cf. -0.2‰ in HEDs) that it formed on a separate parent body. Mineralogical evidence for a different source for NWA 011 (and the paired specimens 2400, 2976, and

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4587) comes from its uniquely high Fe/Mn ratio in pyroxene, ~65 cf. 30-40 in other eucrites (Yamaguchi et al., 2002). In addition, Floss et al. (2005) reported high concentrations of Fe^{3+} in ulvospinel and pyroxene. NWA 011 is unshocked and unbrecciated (Fig. 6c), though it appears to be a recrystallized impact breccia (Yamaguchi, 2001; Yamaguchi et al., 2002). Like most eucrites, NWA 011 has pyroxenes with equilibrated Fe/Mg ratios.

Yamaguchi et al. (2002) noted from their analyses that NWA 011 was unusually high in Ti and Fe and low in Si, but other analyses suggest that these elements are close to or within the eucrite range (Floss et al., 2005). Isa et al. (2008) conclude that NWA 011 is significantly depleted in Mn and Cr relative to eucrites and enriched in siderophiles (e.g., 180 ppm Ni), from which they infer some projectile contamination. Note that the large difference between the oxygen isotopic compositions of NWA 011 and normal eucrites cannot plausibly be attributed to projectile contamination as it would require over 50% contamination from an unknown type of achondrite projectile.

Isotopically, NWA 011 shows two other kinds of anomalies. It has ^{50}Ti and ^{54}Cr excesses like those in CR chondrites whereas other differentiated meteorites show ^{50}Ti and ^{54}Cr deficits (Trinquier et al., 2007a,b). On the $^{53}Cr/^{52}Cr$ vs. $^{55}Mn/^{52}Cr$ diagram, the bulk composition of NWA 011 lies below the eucrite-diogenite whole rock isochron (Bogdanovski and Lugmair, 2003). However, as noted for A-881394, this is not definitive evidence for a separate origin. NWA 011, like A-881394, crystallized early, ~5 Myr after CAIs (Sugiura and Yamaguchi, 2007), so impact processing of NWA 011 to shift its bulk composition seems unlikely. The O, Ti, and Cr anomalies provide convincing evidence that NWA 011 is not from the HED body.

5.1.4. NWA 1240

This unbrecciated vesiculated eucrite was interpreted by Barrat et al. (2003) to be an impact melted cumulate eucrite as it has a positive Eu anomaly and low concentrations of incompatible elements like cumulate eucrites, but it has a porphyritic texture with very fine-grained matrix (Fig. 6d) and unequilibrated pyroxenes. However, NWA 1240 lacks any unmelted clasts, which are characteristic of many impact melts (though admittedly the meteorite is small: 98 g) and one would not expect an impact melt to be formed solely from a single deeply buried lithology such as cumulate eucrites. The bulk Fe/Mn, Ga/Al, and Na/Al ratios of NWA 1240 appear normal for eucrites, but both Na and Al appear low. Plagioclase compositions are unusually high in Mg and Fe. The bulk CaO in NWA 1240 is low for eucrites (8.1 wt.% vs. 8.4-11.1 in eucrites), and FeO is high for cumulate eucrites (20.2 vs. 12-17) (Kitts and Lodders, 1998).

NWA 1240 shows anomalous $\Delta^{17}O$ and $\delta^{18}O$ values: the former lies 4σ below the mean ED value and the latter is 5σ below the mean value of the 12 normal eucrites. One might attribute the shift in $\Delta^{17}O$ to contamination by 1% of carbonaceous chondrite projectile but this would raise the Ni concentration to ~100 ppm and yet only 5 ppm Ni is present (Barrat et al., 2003). In addition, such an admixture would not shift the $\delta^{18}O$ value sufficiently to account for the observed value. An impact melt contaminated by an achondritic projectile with a unique oxygen isotopic composition might account for the oxygen isotopic composition of NWA 1240, but unless the HED body is heterogeneous, a separate body for NWA 1240 is a much simpler and more plausible alternative.

5.1.5. Pasamonte

Pasamonte is the only anomalous eucrite that is a breccia (Fig. 6e). Greenwood et al. (2005) inferred that its anomalously high $\Delta^{17}O$ value was due to the addition of 3% of ordinary chondrite material. In support they cited Metzler et al. (1995), who found an equilibrated clast in Pasamonte and inferred from its siderophile concentrations that it was derived from an impact melt contaminated with either H or CI chondrite material. However, Wiechert et al. (2004) argued that Pasamonte itself could not have been contaminated by 1-3% of ordinary chondrite material as this would have raised concentrations of Ni and Ir and other siderophiles to levels that are ten times higher than observed.

Our analyses of a black clast, the light fragmental matrix, and a third uncharacterized Pasamonte sample give $\Delta^{17}O$ values that are indistinguishable from one another (Table 2) and from the data in Greenwood et al. (2005) and Wiechert et al. (2004), after allowance for the systematic offset between labs (Table 3). We infer that the basaltic material in Pasamonte was derived from a single isotopically homogeneous source. Given that Pasamonte shows none of the textural or chemical characteristics expected for an impact melt and lacks chemical evidence for contamination by chondritic projectiles, its anomalous oxygen isotopic composition is unlikely to reflect such contamination.

Unlike most eucrites, which have been metamorphosed and contain compositionally equilibrated pyroxenes, Pasamonte contains pyroxenes with extensive igneous Mg/Fe zoning and it is classed as a rare type 2 eucrite on the Takeda-Graham type 1-6 scale of metamorphism (Takeda and Graham, 1991). If Pasamonte comes from an isotopically heterogeneous HED parent body, one might expect to find other unmetamorphosed eucrites with similarly anomalous oxygen isotopic compositions. Alternatively, if all unequilibrated eucrites come from bodies that have oxygen isotopic compositions that are homogeneous and unlike the normal eucrite-diogenite value, then even eucrites with a few unequilibrated clasts should have aberrant $\Delta^{17}O$ values. Instead, we found that the seven unmetamorphosed eucrites and polymict eucrites with unmetamorphosed clasts that we selected for comparison with Pasamonte have $\Delta^{17}O$ values that are indistinguishable from those of "normal" eucrites lying within $\pm 2\sigma$ of the mean value; none have values like those in Pasamonte or even intermediate in nature. This argues against Pasamonte originating on an isotopically heterogeneous HED parent body.

The composition of Pasamonte does not appear abnormal for a eucrite (Kitts and Lodders, 1998), although Ni and Ir concentrations are at the high end of the eucrite range. The mean Fe/Mn ratio in Pasamonte's pyroxene (29) lies at the low end of the eucrite range (28-40; Lentz et al., 2007), and its chromite composition appears to be exceptional with very high Al_2O_3 (18 wt.% vs. 7-9% in other eucrites) and very low TiO_2 (1.4 wt.% vs 3-6% in eucrites) (Bunch and Keil, 1971; Mittlefehldt et al., 1998).

If Pasamonte formed on Vesta, it must be derived from a unique region that was homogeneously contaminated with an unknown type of projectile, for which we see no evidence in the HEDs. A more plausible explanation is that Pasamonte comes from another body.

5.1.6. PCA 91007

The $\Delta^{17}O$ value of PCA 91007 (-0.197±0.008; 2× SEM) lies 5σ from the mean eucrite-diogenite value and is indistinguishable from that of Pasamonte (-0.204±0.004; 2× SEM). The $\delta^{18}O$ values

of these two eucrites are also indistinguishable. Although PCA 91007 has been classified as a brecciated eucrite, it is largely unbrecciated (Warren et al., 1996b,c). Some regions appear to be truncated by deformation surfaces, but its fine-grained igneous texture is largely preserved (Fig. 6f). PCA contains vesicles, like Ibitira (Gomes and Keil, 1980; McCoy et al., 2006), but unlike Ibitira, it does not have sub-eucrite levels of alkalis. Its concentration of Ni, Os, and Ir (Warren 1999) are high for a basaltic eucrite and approach the levels in polymict eucrites, as in Pasamonte. However, as noted for Pasamonte, these levels are much lower than would be expected if the oxygen anomaly were caused by contamination with an ordinary chondrite projectile. On balance, we infer that PCA 91007 and Pasamonte could be derived from the same body, which is probably not Vesta. Although the main group pallasites have a mean $\Delta^{17}O$ value of -0.187±0.018 (2σ), which is close to those of PCA 91007 and Pasamonte, the absence of plutonic achondrites with the same $\Delta^{17}O$ value suggests that main group pallasites are not from the same body.

5.2. Comparisons between the anomalous eucrites and other HEDs

To evaluate the frequency of achondrites with anomalous oxygen isotopic composition among the various HED classes, we list in Table 4 the numbers of meteorites in each class (see section 2), the numbers with oxygen isotopic compositions analyzed using laser fluorination techniques, and the names of the six samples with anomalous oxygen isotopic compositions. Five of the six are unbrecciated, though the three eucrites with recrystallized textures could once have been breccias. The exception is Pasamonte, which is unusual in having unequilibrated pyroxenes. Four of the anomalous HEDs are classed as non-cumulate eucrites and two as cumulate eucrites, although as noted above, neither NWA 1240 nor A-881394 has the texture of a cumulate eucrite. Table 4 shows that the two groups with anomalous samples account for only ~7% of HEDs.

We did not identify any diogenites or brecciated basaltic eucrites with equilibrated pyroxenes that have anomalous oxygen isotopic compositions. Howardites with endogenous oxygen isotopic anomalies would be more difficult to recognize in view of their small admixture of carbonacous chondrites. We anticipate that more unbrecciated basaltic eucrites with anomalous oxygen isotopic compositions will be discovered, especially as the list in the Meteoritical Bulletin Database (see http://tin.er.usgs.gov/meteor/metbull.php) is incomplete. Seven such eucrites with precise oxygen isotopic compositions are classified in the Database as monomict eucrite, eucrite breccia, or just plain eucrite (see footnotes to Table 4).

The six eucrites with anomalous oxygen isotopic compositions have several properties that are uncommon among monomict non-cumulate eucrites but relatively common among unbrecciated non-cumulate eucrites. Table 5 compares some of these properties of the six anomalous eucrites with those of seven unbrecciated non-cumulate eucrites that we found to have normal oxygen isotopic compositions. Although three of the six anomalous eucrites have vesicles, they are not unique to anomalous eucrites, as one of the seven normal eucrites also has vesicles. Both normal and abnormal groups contain members with unequilibrated pyroxenes, which are rare among eucrites. Although eucrites are commonly shocked, 12 of the 13 in Table 5 are unshocked; QUE 97053 is the only one with pervasive evidence for shock. The Ar-Ar ages of the eucrites in Table 5 are also unusual: all but one exceeds 4.45 Gyr, although the vast majority of HEDs have Ar-Ar

ages of 3.4 to 4.1 Gyr (Bogard, 1995; Bogard and Garrison, 2003). Possible implications of these Ar-Ar ages are discussed below.

Fe/Mn ratios, either bulk or pyroxene values, are useful for distinguishing basalts from different planetary bodies (Papike 1998; Papike et al., 2003; Mittlefehldt 2005). Table 5 shows that one of the six anomalous eucrites, NWA 011, has an Fe/Mn ratio (~65) that clearly lies outside the range observed for normal eucrites of 28-40; Ibitira's ratio lies at the high end of this range (Lentz et al., 2007; Mayne et al., 2009). Chemical compositions of some of the abnormal eucrites are outside the normal eucrite range. Ibitira and A-881394, for example, both have uniquely low Na contents, much lower than in normal eucrites, which are already more depleted in Na than any other planetary basalts. NWA 1240 appears to have a Ca concentration below the normal eucrite range. PCA 91007, Pasamonte and NWA 011 appear to have rather high levels of siderophiles compared to normal basaltic eucrites. However, some of the normal eucrites like GRA 98098 have anomalous compositions also. The $\delta^{18}O$ values of four of the six anomalous eucrites are within $\pm 2\sigma$ of the mean value for normal eucrites: only NWA 011 and NWA 1240 plot outside at 7σ and 5σ below the mean, respectively.

5.3. Source of eucrites with anomalous oxygen isotopic compositions

Wiechert et al. (2004) argued that the eucrites with anomalous oxygen compositions came from an isotopically heterogeneous HED body, as their oxygen isotopic analyses suggested there was overlap between the $\Delta^{17}O$ values of the normal and anomalous eucrites (Fig. 1), contrary to our data (Figs. 2, 5). Two ways have been suggested for creating or preserving isotopically anomalous basalts. If eucrites were partial melts from an isotopically heterogeneous body, we would expect to find related isotopically heterogeneous residues, like ureilites. However, impacts that excavated the HED body to considerable depths have failed to reveal any traces of isotopically heterogeneous residue material. Without such complementary material it is difficult to believe that isotopically heterogeneous basalts could have been formed this way.

Another possible mechanism for preserving isotopic heterogeneity on the HED body is through an unmelted outer shell that might have generated anomalous basalts after core formation or contaminated normal basalts (Wiechert et al., 2004). However, as Mittlefehldt (2005) notes, such an unmelted chondritic layer would be enriched in metallic Fe,Ni, and liable to founder and mix with a convecting molten interior. No trace of such a layer has been found even though we have several eucrites like ALH 81001 that crystallized near the surface of the HED body and have normal oxygen isotopes. However, a possible piece of evidence favoring the preservation of isotopic heterogeneity in the HED body is that Rai et al. (2005) found mass-independent S isotopic effects in HEDs that they attributed to photochemical reactions in the solar nebula (Thiemens, 2006).

Small anomalies in $\Delta^{17}O$ can be produced from an isotopically homogeneous parent body if there are mass-dependent geological processes operating that have different slope factors (λ). For example, silica and garnet samples that formed under vastly different pressures and temperatures appear to show small (~0.5%) differences in slope factors for oxygen isotopic fractionation (Rumble et al., 2007). The eucrites are composed almost entirely of igneously formed minerals but here is some evidence from quartz veins in Serra de Mage for early aqueous alteration on

Vesta (Treiman et al., 2004). However, this eucrite appears to have a normal $\Delta^{17}O$ value (Wiechert et al., 2004). Furthermore, the magnitude of the observed $\Delta^{17}O$ anomalies, even in NWA 1240, which has the smallest anomaly of the six isotopically aberrant eucrites, seems far beyond the reach of mass-dependent processes with different slope factors without resorting to a sequence of large scale processes, probably requiring other phases like water (e.g. Young et al., 2002).

Although the cosmic ray exposure ages of HEDs indicate that most come from a few impacts during the last 50 Myr (Welten et al., 1997), earlier impacts appear to have mixed Vesta's surface very thoroughly. All HED samples that contain solar wind gases are howardites suggesting that impact mixing on Vesta thoroughly mixed eucrites and diogenites over the surface after deep excavation of the mantle. Because the HED breccias are isotopically normal except for the few samples contaminated with carbonaceous chondrites (Wiechert et al., 2004; Greenwood et al., 2005), it is appears unlikely that the anomalous eucrites are simply coming from poorly sampled regions of Vesta's surface.

One factor that increases the plausibility that eucrites with anomalous oxygen isotope compositions may come from separate bodies is that HED meteorites are located in a crowded region of oxygen isotope space occupied by many unrelated differentiated meteorites (Franchi, 2008). The oxygen isotopic compositions of HEDs were considered by Clayton and Mayeda (1996) to be indistinguishable (or "virtually indistinguishable") from those of angrites, main-group pallasites, mesosiderites, and IIIAB iron meteorites, consistent with a single parent body. However, a ten-fold increase in the precision of $\Delta^{17}O$ measurements has allowed the angrites and main-group pallasites to be clearly resolved from HEDs (Greenwood et al., 2005, 2006, 2008b). Whether the mesosiderites and HEDs, which have overlapping oxygen isotopic compositions, come from the same or closely related bodies is not known with any certainty (Rubin and Mittlefehldt, 1993; Greenwood et al., 2006; Yamaguchi et al., 2006). Oxides in IIIAB irons have not yet been analyzed with high precision, but these irons are unlikely to come from the HED or main-group pallasite body as they cooled faster than main group pallasites underneath a layer of silicate that was only a few kilometers thick (Goldstein et al., 2009). Thus, at least three groups of differentiated meteorites plus a number of brachinites, IAB irons, winonaites, aubrites, and some ungrouped irons and differentiated meteorites plot in or near the oxygen isotope region shown in Fig. 2, even though none comes from the HED parent body. This high density of grouped and ungrouped meteorites increases the chances that the eucrites with anomalous oxygen isotopic compositions are not from Vesta.

The anomalous eucrite, NWA 011, is clearly from a separate body as it has unique excesses of ^{50}Ti and ^{54}Cr (Trinquier et al., 2007a, b) in addition to its unique oxygen isotopic composition and Fe/Mn ratio. For Ibitira and A-881394, the evidence for a separate body comes chiefly from their $\Delta^{17}O$ values. These are so far from the HED value that separate parent bodies seem very plausible for both meteorites. In the case of NWA 1240, PCA 91007, and Pasamonte, which all have $\Delta^{17}O$ values 4-5σ from the mean of normal eucrites, the evidence for separate bodies is weaker but still significant. We conclude that NWA 011, Ibitira, and A-881394, are probably derived from three separate bodies and that NWA 1240, PCA 91007 and Pasamonte may come from two more. With the possible exception of Ibitira, which has an oxygen isotopic composition that matches those of

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the angrites, the anomalous eucrites are not linked in any way with other types of differentiated meteorites.

Palme (2002) speculated that NWA 011 was derived from Mercury, but chemical, mineralogical, and isotopic similarities with the eucrites favor a smaller, Vesta-like source (Nyquist et al. 2003a, Bogdanovski and Lugmair 2004). In addition, NWA 011 and A-881394 have Al-Mg and Mn-Cr isochron ages of 3-5 Myr after CAIs, like fine-grained angrites (Wadhwa et al., 2005; Sugiura and Yamaguchi, 2007), clearly favoring an origin from asteroids, not from planets, which have much younger surfaces. Since the number of eucrites with anomalous oxygen isotopic compositions now exceeds the number of uncharacterized terrestrial planets, Vesta-like bodies should be considered as more plausible sources for the eucrites with anomalous oxygen isotopic compositions. The sizes of these Vesta-like bodies are poorly constrained, but bodies 200 km or more across were probably large enough to retain partial melts and the ^{26}Al, which would have been necessary for further heating (Wilson and Keil, 1991).

How many Vesta-like bodies could have existed in the asteroid belt and how could they have been removed, if Vesta is the sole intact basaltic asteroid (Pieters et al., 2005)? If they were battered to bits by impacts over billions of years, as Burbine et al. (1996) proposed for the parent bodies of differentiated meteorites, how did Vesta's crust survive, and where are the diogenites, pallasites and iron meteorites with Δ^{17}O values that match those of the anomalous eucrites? With the possible exception of Pasamonte and PCA 91007, which have Δ^{17}O values close to those of main-group pallasites (see §5.1.6), we lack igneous meteorites with Δ^{17}O values that match those of the anomalous eucrites.

Unless Vesta was a unique body that was somehow emplaced after the asteroid belt had largely formed, it seems likely that ~10^{3-4} Vesta-like bodies once existed in the belt, as the primordial mass of asteroids is thought to have been ~10^{3-4} higher than at present. These bodies would have been largely removed by perturbations from protoplanets and Jupiter at ~4.5 Gyr, with perhaps a smaller mass loss during the Late Heavy Bombardment (Petit et al., 2002; O'Brien et al., 2007). In both cases, the asteroids would have been lost dynamically through orbital resonances, not through collisional grinding. Thus, it is possible that we have samples from the crusts of several other Vesta-like bodies, even though these bodies no longer exist and we lack other igneous meteorites with Δ^{17}O values that match those of the anomalous eucrites. Below we discuss the Ar-Ar ages and shock and breccia characteristics of isotopically normal and anomalous eucrites, which support this hypothesis.

5.4. Origin of unbrecciated eucrites

Unbrecciated basaltic eucrites are mostly unshocked (Mayne et al., 2009), suggesting that they avoided the impacts that caused both shock and brecciation. The rare unbrecciated isotopically normal eucrites could represent the few lucky rocks that survived unscathed on Vesta for four billion years. However, their Ar-Ar ages suggest they many have a very different history. Bogard and Garrison (2003) found that about two-thirds of their sample of unbrecciated eucrites, both cumulate and non-cumulate, had Ar-Ar ages of 4.48±0.02 Gyr. All the 11 eucrites in the 4.48 Gyr cluster appear to have normal oxygen isotopic compositions except for EET 87520 and Y-7308, which have not yet been analyzed, and Ibitira. Even allowing for possible ^{40}K half-life

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errors that might increase the Ar-Ar age by ~30 Myr, this age is still ~50 Myr after the eucrites crystallized (e.g., Sanders and Scott, 2007b). Brecciated eucrites, which are commonly shocked, show consistently younger Ar-Ar ages which are mostly between ~3.4 and 4.1 Gyr, overlapping the Late Heavy Bombardment of the Moon (Bogard, 1995).

Bogard and Garrison (2003) inferred that the 4.48 Gyr Ar-Ar ages of the 11 eucrites may have resulted from a major impact on Vesta that excavated deeply-buried cumulate eucrites and unbrecciated and metamorphosed basaltic eucrites from the hot crust, allowing them to cool rapidly. To explain why the 4.48 Gyr Ar-Ar ages of these eucrites, which are nearly all unshocked, were not reset by impacts during the Late Heavy Bombardment of the Moon, Bogard and Garrison (2003) suggested that these rocks were ejected from Vesta at 4.48 Gyr and reaccreted to form a much smaller asteroid. Although many smaller asteroids would have been easily demolished during the Late Heavy Bombardment, those that survived would not have contained many shocked rocks. Bogard (1995) argued from the Ar-Ar ages of HEDs and ordinary chondrites that only bodies as large as Vesta or the Moon could acquire a crust largely composed of rocks and debris that were impact-heated during the Late Heavy Bombardment.

Scott and Bottke (2007) used similar arguments to those of Bogard and Garrison (2003) to explain why angrites are unshocked and unbrecciated unlike eucrites, which are commonly shocked and brecciated, even though many angrites have textures indicating they crystallized rapidly near the surface. One might surmise that smaller bodies are more efficient at producing shocked meteorites and meteorite breccias as their surface-to-volume ratios are much higher than those of larger bodies. However, two factors oppose this effect. First, shocked rocks on smaller bodies are more likely to be accelerated above the escape velocity. A body 10 km across, for example, receives 50× more kinetic energy from projectiles per kg of target each year than Vesta, but its escape velocity is 50× smaller. Second, the maximum impact energy deposited per kg of target during a near-catastrophic collision will be ~100× higher for Vesta than for a 10 km body (Love and Ahrens, 1996). Because of the size distribution of projectiles in the asteroid belt, the large rare events do much more damage to an asteroid than all of the more numerous smaller cratering events. If an appreciable fraction of 10 km bodies can survive for 4.5 Gyr, as Scott and Bottke (2007) inferred, then rocks from Vesta could have been safely stored for 4.5 Gyr in a 10 km body, which was broken up in the last ~50 Myr to provide unshocked and unbrecciated eucrites with 4.5 Gyr Ar-Ar ages.

The absence of eucrite breccias and shocked eucrites with Ar-Ar ages of ~4.48 Gyr or older suggests that these samples were not abundant on Vesta's surface at that time. Several factors may have been responsible. High ambient temperatures in the crust would have ensured that rocks like EET 90020 that were involved in impacts prior to 4.48 Gyr were quickly annealed back into unbrecciated rocks (Yamaguchi et al., 2001). In addition, planetesimals as large as Ceres may have formed by gravitational collapse via a streaming instability in a turbulent nebula (Johansen et al., 2007), rather than by binary accretion of km-sized and larger planetesimals. In this case, there may have been numerous Vesta-sized asteroids but few smaller bodies that could fragment and shock their surface rocks, form breccias, or even catastrophically disrupt them.

The Bogard-Garrison model for the ~4.48 Gyr old unbrecciated eucrites with normal oxygen isotopic compositions provides a plausible explanation for the chemical and petrographic

similarities between the anomalous eucrites and the unbrecciated eucrites with normal oxygen isotopes (Table 5). The anomalous eucrites could have avoided being shocked and brecciated during the Late Heavy Bombardment because at that time they were residing in small asteroids (~10 km in diameter) that had been derived earlier from Vesta-sized bodies. If the iron and stony-iron meteorites come from bodies that formed inside 2 AU and were eviscerated by protoplanetary impacts before reaching the asteroid belt (Bottke et al., 2006; Asphaug et al., 2006), this would help to explain why some differentiated asteroids were catastrophically destroyed but others were not. Vesta and the parent bodies of the anomalous eucrites might have escaped catastrophic disruption because they formed in the asteroid belt or because they were scattered there without being eviscerated.

6. SUMMARY AND CONCLUSIONS

Our results show that 18 of the 23 eucrites and diogenites that we analyzed, including Caldera, which was previously inferred to have an anomalous oxygen isotopic composition (Wiechert et al., 2004), have $\Delta^{17}O$ values consistent with an origin on an isotopically homogenized body. The other five meteorites are outliers, with $\Delta^{17}O$ values located more than 4 sigma from the HED mean. They include Ibitira and Pasamonte, and three eucrites not previously known to have anomalous oxygen, namely A-881394, NWA 1240 and PCA 91007. We infer that contamination by chondritic projectiles during impacts on Vesta cannot account for the anomalies, and that the five outliers plus NWA 011 (which we did not analyze) may come from five different parent bodies (Pasamonte and PCA-91007 may come from the same body).

For NWA 011, the size of the oxygen isotopic anomaly, the ^{50}Ti and ^{54}Cr excesses, and the high Fe/Mn ratio provide unambiguous evidence for a separate parent body. For Ibitira and A-881394, the oxygen isotopic anomalies are smaller but together with the high Fe/Mn ratio of Ibitira and the antiquity and Mn-Cr isotopic anomalies of A-881394 they provide compelling evidence for two additional parent bodies. In the case of NWA 1240, PCA 91007, and Pasamonte, the existence of their oxygen isotopic anomalies is well established, but their relatively small size (4-5σ) and the more ambiguous nature of their mineralogical and chemical anomalies provide somewhat weaker evidence for separate parent bodies.

We would prefer that the term "eucrite" be used merely as a rock type, like "pallasite", with no implication about the parent body, consistent with the meaning of its Greek root (eukritos: easily distinguished). Then, NWA 011, Ibitira, and A-881394 could be simply classified as ungrouped eucrites. However, because the concept of an HED parent body, almost certainly Vesta, is really well established, and because the letter E in HED stands for eucrite, any meteorite referred to as a eucrite could be taken as a sample of Vesta. Consequently, NWA 011, Ibitira, and A-881394 are probably best referred to as "ungrouped basaltic achondrites", at least until the term "eucrite" is widely used in the way we suggest. For NWA 1240, PCA 91007, and Pasamonte, the term "anomalous eucrite" seems appropriate, although an origin on the parent body of the normal eucrites seems unlikely.

Given that several meteorite types including main-group pallasites and angrites have oxygen isotopic compositions that were previously indistinguishable from those of HEDs, it is not surprising that the anomalous oxygen isotope compositions of five of the six anomalous eucrites

were only discovered by laser-assisted fluorination techniques. For three of the isotopically anomalous eucrites, the differences between their $\Delta^{17}O$ values and those of normal eucrites and diogenites are comparable to inter-laboratory differences between published laser-assisted oxygen isotopic analyses for normal eucrites. This highlights the need for better standardization procedures and the problems in combining existing data for HEDs from different labs.

Since the chemical compositions of basaltic eucrites cluster around the low-pressure pseudoperitectic composition for olivine, pigeonite and plagioclase (e.g., Ruzicka et al., 1997), eucritic basalts from asteroids of broadly similar sizes and oxidation states should be indistinguishable on the basis of their major element mineral composition and mineralogy, as is observed for the isotopically anomalous eucrites.

The existence of many Vesta-like bodies in the asteroid belt is entirely consistent with current models for the asteroid belt in which the primordial mass of asteroids was 10^{3-4} times its current mass. Removal of these Vesta-like bodies by orbital excitation of Jupiter and protoplanets rather than collisional grinding accounts for the absence of interior samples of the Vesta-like bodies and the preservation of Vesta's basalt-like surface. We suggest that the six anomalous eucrites largely escaped post-metamorphic shock and brecciation as they were sequestered in small asteroids during the Late Heavy Bombardment when the surface of Vesta was battered by impacts to produce the shocked and brecciated features typical of most HED meteorites.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data associated with this article can be found in the online version, at doi: 10.1016 etc.

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Table 1. Names of 18 eucrites and 4 diogenites analyzed for oxygen isotopic composition with classifications, sources, and reasons for selection.

Name[a]	Class[b]	Source[c]	Why analyzed?	References
ALHA81001	Unbr. non-cumulate	,45	Quench texture; unbrecciated	Warren et al. (1996c)
A-881394	Cumulate-anom.	,76	Granulitic texture; old age	Takeda et al. (1997), Nyquist et al., (2003b)
Caldera	Unbr. non-cumulate	SI 6394	Anomalous O isotopes	Wiechert et al. (2004) Boctor et al. (1994)
EET 90020	Unbr. non-cumulate	,48	Rare eucrite	Yamaguchi et al. (2001)
GRA 98098	Unbr. non-cumulate	,53	Unusual eucrite	Mittlefehldt & Lee (2001);
GRA 98108	Diogenite	,24	Rare unbr.; 30% olivine	Righter (2001)
GRO 95555	Diogenite	,35	Unusual unbr. diogenite	Papike et al. (2000)
Ibitira	Unbr. non-cumulate	Burton K. W. Oxford Univ.	Unique eucrite, Aberrant O isot.	Mittlefehldt (2005) Wiechert et al. (2004)
NWA 1000	Unbr. non-cumulate	UCLA	Extraordinarily unequilibrated	Warren (2002)
NWA 1240	Cumulate-anom.	Barrat J. A.	Unique eucrite	Barrat et al. (2003)
NWA 1461	Diogenite	UCLA	Mg-rich	Bunch et al. (2007)
Pasamonte[d]	Polymict non-cumulate	SI 897 BM1937.379	Anomalous O isotopes	Wiechert et al. (2004) Greenwood et al. (2005)
PCA 91007	Unbr. non-cumulate	,2	Unusual vesicular eucrite	Warren et al. (1996c)
QUE 97053	Unbr. non-cumulate	,21	Old Ar-Ar age	Bogard & Garrison (2003)
Y-74159	Polymict	,66	Pasamonte-like clasts	Takeda et al. (1983)
Y-74450	Polymict	,67	Pasamonte-like clasts	Takeda et al. (1983)
Y-75011	Polymict	,63	Pasamonte-like clasts	Takeda and Graham (1991)
Y-75032	Diogenite	,55	Unusual diog.	Takeda and Mori (1985)
Y-790260	Polymict	,55	Pasamonte-like clasts	Antarctic Meteorite Data Base[e]
Y-791192	Polymict	,72	Unique breccia	Saiki et al. (2001)
Y-82202	Polymict	,73	Unusual eucrite	Buchanan et al. (2005)
Y-981651	Unbr. non-cumulate	,77	Unequil. eucrite	Warren (2003)

[a] Abbreviations: A Asuka, ALH Allan Hills, EET Elephant Moraine, GRA Graves Nunataks, GRO Grosvenor Mountains, NWA Northwest Africa, PCA Pecora Escarpment, QUE Queen Alexandra Range, Y Yamato.
[b] Classifications from listed reference or Meteoritical Bulletin Database (see http://tin.er.usgs.gov/meteor/metbull.php).

[c] Source abbreviations: SI, U.S. National Museum; BM, Natural History Museum, London; UCLA, University of California at Los Angeles. Asuka and Yamato specimens are from NIPR, Tokyo; other Antarctic specimens are from Meteorite Working Group, NASA-JSC, Houston.

[d] Although Pasamonte appears to lack diogenite material, it is listed as polymict as it contains a small fraction of diverse clasts (Metzler et al., 1995).

[e] See http://metdb.nipr.ac.jp/am_db_public.

Table 2. Oxygen isotopic compositions[a] of 10 non-cumulate eucrites, 2 anomalous cumulate eucrites, 6 polymict eucrites, 4 diogenites, and separated phases in NWA 1240.

SAMPLE[b]	N[c]	$\delta^{17}O$ ‰	1σ	$\delta^{18}O$ ‰	1σ	$\Delta^{17}O$ ‰	1σ
Non-cumulate Eucrites (Basaltic Eucrites)							
ALHA81001	2	1.767	0.004	3.832	0.002	-0.241	0.003
Caldera	2	1.804	0.020	3.911	0.030	-0.246	0.004
EET 90020,48	2	1.690	0.047	3.689	0.098	-0.244	0.004
GRA 98098,53	2	1.679	0.007	3.640	0.022	-0.229	0.019
Ibitira	4	1.959	0.016	3.868	0.044	-0.069	0.017
NWA 1000	2	2.001	0.011	4.245	0.011	-0.224	0.005
EATG residue	2	1.883	0.097	4.056	0.180	-0.243	0.002
Pasamonte (BM)	8	1.797	0.052	3.817	0.107	-0.204	0.010
dark clast (SI)	2	1.853	0.064	3.913	0.115	-0.198	0.004
light matrix (SI)	2	1.769	0.037	3.767	0.054	-0.206	0.009
EATG residue (BM)	1	1.780		3.799		-0.211	
Mean	13	1.800	0.052	3.823	0.100	-0.204	0.008
PCA 91007, 2	3	1.720	0.080	3.657	0.139	-0.197	0.007
HCl residue	2	1.766	0.001	3.767	0.033	-0.208	0.016
Mean	5	1.738	0.062	3.701	0.116	-0.202	0.011
QUE 97053,21	3	1.653	0.012	3.585	0.048	-0.226	0.014
Y-981651	2	1.688	0.025	3.682	0.024	-0.242	0.013
Cumulate Eucrite - Anom.							
A-881394	3	1.939	0.030	3.943	0.081	-0.128	0.013
EATG residue	2	1.884	0.023	3.829	0.006	-0.123	0.019
HCl residue	1	1.890		3.806		-0.105	
Mean	6	1.912	0.036	3.882	0.084	-0.122	0.015
NWA 1240	4	1.324	0.057	3.043	0.105	-0.271	0.007
EATG residue	1	1.363		3.097		-0.260	
HCl residue	2	1.334	0.042	3.076	0.064	-0.279	0.008
Mean	7	1.332	0.046	3.060	0.082	-0.272	0.009
Matrix, grey	1	1.378		3.164		-0.280	
Matrix, light grey	1	1.325		3.054		-0.276	
Pyroxene, clear	1	1.229		2.859		-0.270	
Pyroxene, translucent	1	1.279		2.917		-0.250	
Polymict Eucrites							
Y-74159,66	2	1.660	0.011	3.607	0.006	-0.230	0.008
Y-74450,67	2	1.680	0.017	3.668	0.034	-0.242	0.001
Y-75011,63	2	1.665	0.008	3.634	0.005	-0.239	0.011
Y-790260	3	1.733	0.044	3.794	0.110	-0.255	0.016
Y-791192,72	2	1.607	0.003	3.521	0.001	-0.238	0.002
Y-82202	2	1.617	0.028	3.553	0.078	-0.246	0.013
Diogenites							
GRA 98108,24	2	1.447	0.020	3.233	0.030	-0.247	0.004
GRO 95555,35	4	1.407	0.145	3.171	0.255	-0.255	0.015
NWA 1461	2	1.556	0.050	3.443	0.095	-0.249	0.000
HCl residue	2	1.602	0.021	3.524	0.035	-0.246	0.002
Mean	4	1.579	0.041	3.483	0.075	-0.247	0.002
Y-75032,55	2	1.446	0.053	3.210	0.123	-0.237	0.011

[a] $\delta^{17}O$ and $\delta^{17}O$ values are reported in the standard notation; $\Delta^{17}O$ is calculated using the linearized format of Miller (2002); see text.
[b] Abbreviations as in Table 1. Samples untreated unless otherwise noted.
[c] Number of replicate analyses. These are listed in the Electronic Annex Table EA1.

Table 3. Comparison of $\Delta^{17}O$ values (‰) for eucrites (E) and diogenites (D) with published data.

Samples	This work	Greenwood et al. (2005)	Wiechert et al. (2004)	Greenwood −Wiechert
E & D[b] ±2σ	-0.242±0.016[a]	-0.239±0.014 [a]	-0.218±0.024	-0.021
2 × SEM	±0.004	±0.003	±0.004	±0.006
No. Falls	0	17	11	
No. finds	17	0	13[c]	
No. anal.	38	43	29	
Nine E & D falls[b] ±2σ		-0.239±0.012 [a]	-0.218±0.018	-0.021
2 × SEM		±0.004	±0.005	±0.007
No. anal.		27	12	
Caldera	-0.246±0.006		-0.189±0.018	
Ibitira	-0.069±0.016		-0.064±0.013	
Pasamonte	-0.202±0.004	-0.205±0.011	-0.184±0.011	

[a] 2σ standard deviations calculated from replicate means for each meteorite rather than from individual analyses.

[b] Eucrites lying >3σ from mean (Ibitira and Pasamonte) are excluded.

[c] ALHA76005 and ALHA78132 are counted as separate finds (though probably paired), and "Binola" is inferred to be an error for "Binda," as there is no Binola meteorite.

Table 4. Number of howardites, eucrites, diogenites by class listed in the Meteoritical Bulletin Database[a]; number analyzed for oxygen isotopes by laser fluorination [b], and classifications of achondrites with anomalous oxygen isotopic compositions.

Class	Number of meteorites	Number with precise oxygen isotopic comp.	Achond. with anomalous O isotopic comp.[c]
Howardites	174	10	0
Monomict non-cumulate eucrites[d]	145	11	0
Unbrecc. non-cumulate eucrites[e]	35	13	PCA 91007, Ibitira
Cumulate eucrites	20	7	NWA 011 A-881394 NWA 1240
Polymict eucrites	141	7	Pasamonte
Other eucrites[f]	132	1	0
Diogenites[g]	177	14	0
Polymict diogenites	8	1	0
Total	831	61	6

[a] http://tin.er.usgs.gov/meteor/metbull.php as of 11-17-08.

[b],Analyzed by Wiechert et al. (2004), Greenwood et al. (2005), Floss et al. (2005), Barrat et al. (2006, 2007, 2008) and this study. Analyses in abstracts and the Meteoritical Bulletin were excluded.

[c] Four howardites contaminated with carbonaceous chondrite are excluded.

[d] Total includes 66 eucrite breccias and NWA 4523 (Barrat et al., 2007).

[e] Total includes Caldera, Chervony Kut, HH 262, NWA 1000, PCA 91007, ALH 81001, EET 90020, Y-981651, and NWA 011 (Floss et al., 2005).

[f] Includes unclassified eucrites, 1 anomalous eucrite and 4 Mg-rich eucrites.

[g] Includes 1 olivine diogenite, and 2 anomalous diogenites.

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Table 5. Comparison of eucrites with abnormal oxygen isotopic compositions with unbrecciated non-cumulate eucrites with normal oxygen isotopic compositions.

Meteorite	Class	Vesi-cles?	Equil./ Unequil.[a]	Ar-Ar age (Gyr)[b]	Fe/Mn ratio[c]	Compositional and other quirks
Abnormal						
A-881394	Unbr. Anom. cumulate	no	Equil.		31	Low Na; An_{98} 4566 Myr Pb-Pb age
Ibitira	Unbr. Non-cumulate	yes	Equil.	4.49±0.02	35-36	Low Na; An_{95} High Ti/Hf
NWA 011	Unbr. Non-cumulate	no	Equil.	3.15±0.03	65-67	Low Mn, Cr; high Fe^{3+}; excess ^{50}Ti, ^{54}Cr
NWA 1240	Unbr. Anom. cumulate	yes	Unequil.		31±6	Low Ca, low $\delta^{18}O$,
Pasamonte	Polymict Brec.[d] Non-cumulate	no	Unequil.	4.45±0.05 4.0±0.1	29±2	Unique breccia of unequil. clasts
PCA 91007	Unbr. Non-cum.	yes	Equil.	≥4.44	34	
Normal						
ALHA81001	Unbr. Non-cum.	no	Equil.		32-34	High Cr, high Mg/Fe
Caldera	Unbr. Non-cum.	no	Equil.	4.49±0.01	30-32	
EET 90020	Unbr. Non-cumulate	no	Equil.	4.49±0.01	31	Complex thermal history
GRA 98098	Unbr. Non-cumulate	no	Equil.	4.49±0.02 4.45±0.01	30-33	High Na, Cr
NWA 1000	Unbr. Non-cum.	no	Unequil.		38	High Ti
QUE 97053	Unbr. Non-cum.	no	Equil.	4.480±0.015	28-35	
Y-981651	Unbr. Non-cum.	yes	Unequil.			Low-Ti? Al-rich pyx.

[a] Eucrites containing pyroxene with equilibrated or unequilibrated Fe/Mg ratio: QUE 97053 from Mayne et al. (2009), others from references in text and Table 1, or Meteorite Bulletin Database (see http://tin.er.usgs.gov/meteor/metbull.php).

[b] Ar-Ar ages from Bogard and Garrison (2003) except for EET 90020 (Yamaguchi et al., 2001), NWA 011 (Bogard and Garrison, 2004), and Pasamonte (see Bogard, 1995). Where two ages are listed the first dates primary cooling and the second, impact degassing. See text for references to other data.

[c] Fe/Mn ratios are from pyroxene analyses by Mayne et al. (2009) except for Ibitira (Mittlefelhdt, 2005), NWA 011 (Yamaguchi et al., 2002; Floss et al., 2005), NWA 1240 (Barrat et al., 2003), Pasamonte (Lentz et al., 2007), and the following for which bulk data were used: A-881394 and PCA 91007 (Warren et al., 1996b), and NWA 1000 (Warren, 2002).

[d] Monomict according to Delaney et al. (1983).

Figure Captions

Fig.1. Histograms showing published $\Delta^{17}O$ values for eucrites and diogenites obtained by laser-assisted fluorination with outliers identified: (a) 29 analyses by Wiechert et al. (2004) of 24 eucrites and diogenites; (b) mean values of 17 eucrites and diogenites from 43 analyses by Greenwood et al. (2005). Horizontal bars show $\pm 2\sigma$ of the individual values and $\pm 2\times$ the standard error of their mean (SEM). The howardite mean in (a) and data for howardite matrix samples in (b) are significantly offset from the mean values for eucrites and diogenites (excluding Ibitira and Pasamonte) because of carbonaceous chondrite projectiles. The mean eucrite-diogenite values in the two studies differ by 0.02‰ because of different laboratory calibration procedures (see section 4.1). The two Pasamonte analyses in (a) appear to lie on the tail end of a skewed distribution for eucrites and diogenites, but in (b), Pasamonte appears quite distinct. Abbreviations: A76: ALHA76005, A78: ALHA78132, Ca: Caldera, and St: Stannern. Main group (MG) pallasite mean from Greenwood et al. (2006).

Fig. 2. Oxygen isotope variation diagram showing mean values of $\Delta^{17}O$ vs. $\delta^{18}O$ for the 18 eucrites, 4 diogenites and the Pasamonte matrix and clast samples listed in Table 1. Line drawn through HED data excludes five eucrite outliers: Ibitira, A-881394, Pasamonte, PCA 91007, and NWA 1240. Angrite data and angrite fractionation line (AFL) are from Greenwood et al. (2005); TFL= terrestrial fractionation line.

Fig. 3. Oxygen isotope variation diagram showing $\Delta^{17}O$ vs. $\delta^{18}O$ for achondrites that were leached in ethanolamine thioglycolate (EATG) or 6M HCl (HCl) and for the unleached samples (Untreat). Unlabelled data are from Fig. 2. Meteorite abbreviations: A: A-881394, P: Pasamonte, PCA: PCA 91007, 1000: NWA 1000, 1461: NWA 1461, 1240: NWA 1240. The oxygen isotopic compositions of the acid leached samples do not differ significantly from those of the corresponding untreated samples, except for NWA 1000, showing that isotopic compositions of the outliers do not result from terrestrial weathering. Compositions of a dark clast in Pasamonte (P-Dark), light matrix (P-Light), and other Pasamonte samples are indistinguishable from one another with respect to $\Delta^{17}O$.

Fig. 4. Oxygen isotope variation diagram showing the mean values of $\Delta^{17}O$ vs. $\delta^{18}O$ for two samples of pyroxene and two residual matrix samples from the anomalous eucrite, NWA 1240. The bulk data for treated and untreated samples of NWA 1240 and the other eucrites and diogenites are from Fig. 3. The pyroxene and matrix data for NWA 1240 confirm that this eucrite has anomalous $\Delta^{17}O$ and $\delta^{18}O$ values, and that the $\delta^{18}O$ anomaly in the whole rock samples was not due to an enrichment of pyroxene in the bulk samples that were analyzed.

Fig. 5. Histogram showing $\Delta^{17}O$ values for eucrites and diogenites from this study and Greenwood et al. (2005). The six eucrites with abnormal oxygen isotopic compositions, NWA 011 (Floss et al., 2005), NWA 1240, Pasamonte, PCA 91007, A-881394, and Ibitira, have $\Delta^{17}O$ values that are >4σ from the values for the other eucrites and diogenites. Data for normal eucrites and diogenites from this study are very similar to those of Greenwood et al. (2005) and in both cases plot within 2σ of the mean value. Angrite data are from Greenwood et al. (2005). Horizontal bars show ±2σ of the individual values and ±2× the standard error of their mean (SEM).

Fig. 6a-e. Photomicrographs of six eucrites with anomalous oxygen isotopic compositions in crossed-polarized transmitted light except for (d), which is in reflected light. All six eucrites appear unshocked and unbrecciated except for Pasamonte (e), which is a fragmental breccia. A-881394 (a), Ibitira (b), and NWA 011 (c) have recrystallized textures (and may have been brecciated prior to recrystallization), whereas NWA 1240 (d), the clasts in Pasamonte (e), and PCA 91007 (f) have mostly fine-grained igneous textures. (Fig. 6c courtesy of A. Yamaguchi.)

Electronic Annex Caption

Electronic Annex Table EA1: Replicate analyses of oxygen isotopic compositions of eucrites and diogenites.

Fig.1

Fig.2

Fig.3
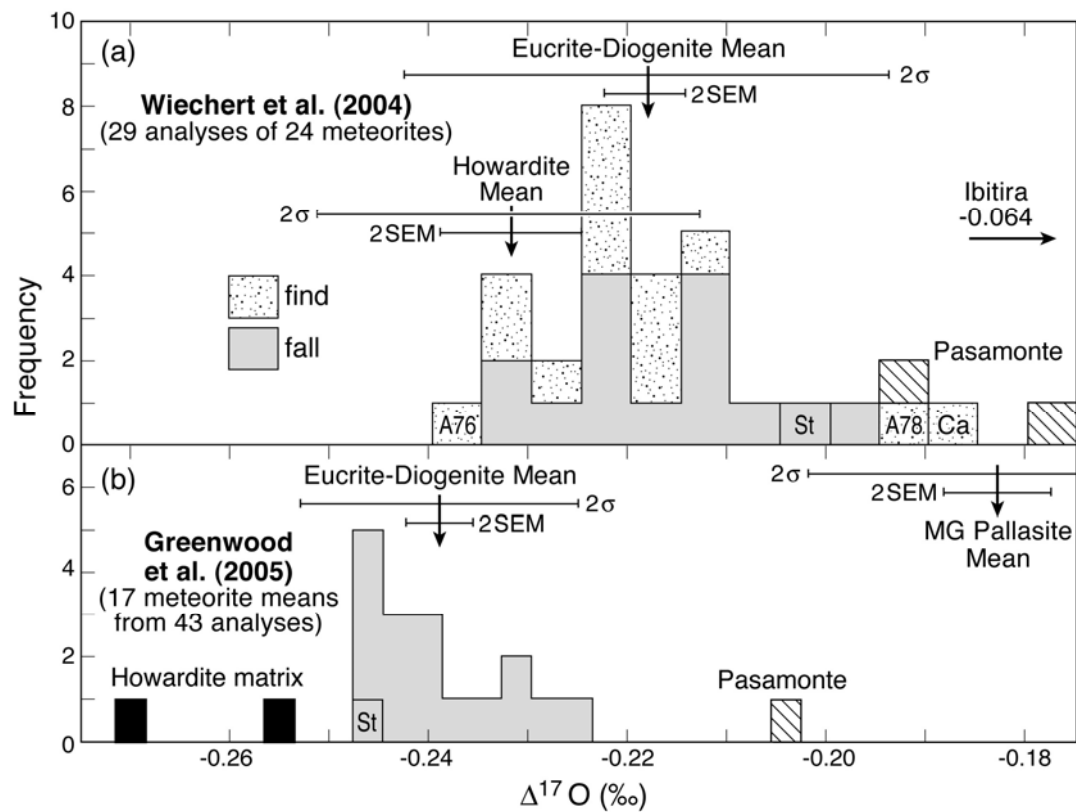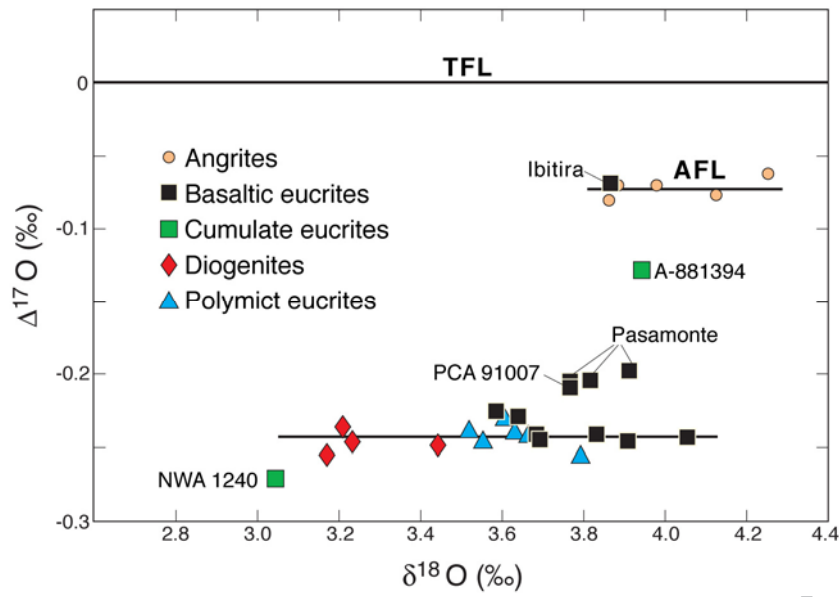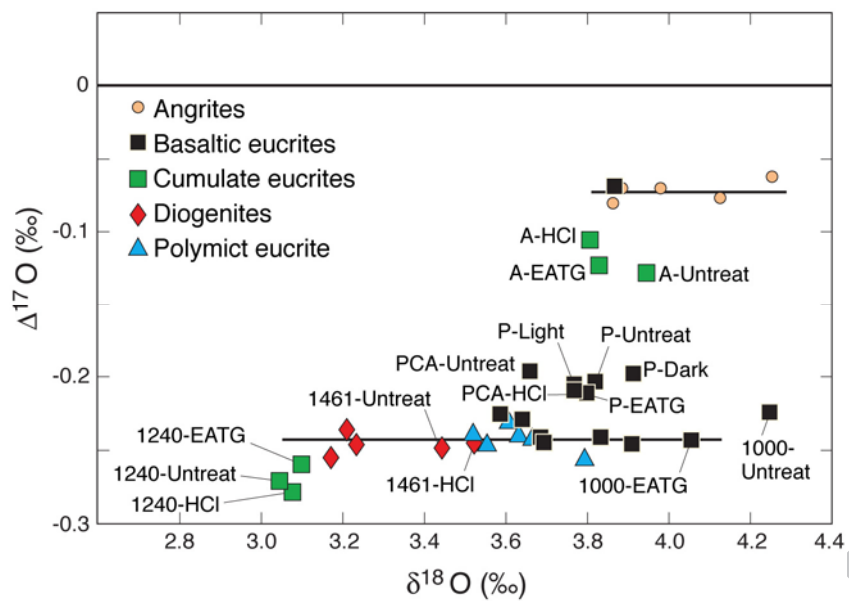
Fig.4

Fig.5

Fig.6

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