Oxygen isotope evidence for rapid mixing of the HED meteorite parent body

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Abstract

The ^{16}O, ^{17}O and ^{18}O abundances of howardites, eucrites, and diogenites have been used to assign them to a single 'HED' parent body, thought to be asteroid 4 Vesta. We report the first evidence of oxygen isotopic heterogeneity among HED meteorites indicating incompletely mixed sources. New high-precision oxygen isotope measurements of 34 HED meteorites reveal that most have the same $\Delta^{17}O'$, consistent with a very rapid early history of large-scale mixing on Vesta. However, howardites are on average very slightly enriched in ^{16}O, whereas Ibitira, Caldera, Pasamonte, and ALHA78132 are ^{16}O-depleted compared to other investigated eucrites. The $\Delta^{17}O'$ of Ibitira is completely different from all other HEDs measured. Some of the results for eucrites and diogenites can be explained by partial melting and rapid mixing of the interior of Vesta. Others require a separate parent body or indicate that parts of the outer layer of Vesta retained some primary isotopic heterogeneity. The oxygen isotopic composition of howardites provides an upper limit for the amount of admixed carbonaceous chondritic material into the HED parent body regolith.
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1. Introduction

The oxygen isotopic compositions of meteorites provide a powerful tool for assessing the provenance of early solar system material. This approach can be used to assess the number of parent bodies of differentiated silicate meteorites or achondrites. The largest group among these meteorites are howardites, eucrites and diogenites, often referred to as HED meteorites. Diogenites are coarse-grained, usually brecciated, cumulate rocks consisting mainly of orthopyroxene. Cumulate eucrites are coarse-grained gabbros, mostly unbrecciated. Non-cumulate or basaltic eucrites formed originally from quickly cooled surface lava flows or shallow intrusions. Most of these eucrites have been buried and metamorphosed. Howardites are polymict regolith breccias consisting of eucrites and diogenites together with sub-

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ordinate quantities of olivine, carbonaceous chondrite xenoliths, and a variety of impact glasses embedded in a fine-grained matrix [1]. Such meteorites provide evidence that some primitive planetary embryos differentiated into a metallic core and partially molten silicate mantle within the first 10 million years of solar system history. However, whether such early planetary bodies were in a relatively primitive state with heterogeneities inherited from accretion [2] or well-mixed perhaps as a result of a magma ocean stage [3] is unclear.

Previously reported oxygen isotope data are consistent with the concept of a single parent body for these three types of meteorites, the data defining a linear array in a three-isotope diagram that lies below the terrestrial fractionation line (TFL) [4,5]. McCord et al. [6] recognized that the reflectance spectrum of asteroid 4 Vesta matches the laboratory spectrum of the basaltic eucrite Nuevo Laredo. Subsequently, it was found that the reflectance spectra of diogenites and howardites could also be related to certain regions on Vesta [7]. That Vesta is the parent body of the HED meteorite group is supported by the discovery of eight smaller bodies. These so-called vestoids bridge the orbital space between Vesta and the 3:1 orbit–orbit resonance with Jupiter, from where the HED meteorites can enter Earth-crossing orbits [8]. The latest evidence in establishing Vesta as the HED parent body has been provided by the Hubble Space Telescope which imaged a huge impact structure covering most of the southern hemisphere of Vesta. This linkage has inspired the development of various models on the formation and differentiation of Vesta as the HED parent body.

Recently, however, it has been shown that at least one basaltic meteorite has a different $\Delta^{17}O'$. This meteorite and also angrites provide evidence for more differentiated meteorite parent bodies than just Vesta, the Moon and Mars [9]. In fact several hundreds of planetary embryos of the size of Vesta may once have existed in what is now the asteroid belt [10]. Those that grew in close proximity should have acquired similar $\Delta^{17}O'$. Published data are consistent with this [4,5]. However, the precision with which such measurements can now be made has improved

greatly. Therefore, it is important to see if such uniformity persists to the high levels of precision presently achievable, or whether heterogeneities can now be resolved.

To evaluate whether HEDs formed on a single or several parent bodies we have determined precise abundances of ^{16}O, ^{17}O and ^{18}O for 34 HED meteorites using a CO_2 laser fluorination technique which yields data that are an order of magnitude more precise than currently available. This also allows us to evaluate whether eucrites formed by melting of poorly mixed primitive material [2] or a homogeneous reservoir such as might be produced in a magma ocean [3].

2. Methods

The oxygen isotope ratios of HED meteorites were measured at the Geophysical Laboratory, Carnegie Institution of Washington. For some samples one to five small fragments with a total mass of 1.9–2.3 mg were reacted in a BrF_5 atmosphere. Powdered samples were melted in vacuum before fluorination in order to avoid losing material by violent reaction of the powder with BrF_5 during laser heating. Surplus BrF_5 and other condensable gases were frozen in liquid nitrogen cold traps. Oxygen was transferred from the metal to the glass line and frozen on a liquid nitrogen-cooled 5 Å molecular sieve. The isotopic composition was measured on mass 32, 33, and 34 on a Finnigan MAT-252 dynamic gas source mass spectrometer. No corrections on mass 33 ($^{17}O^{16}O$) were made because the high mass resolution of the MAT-252 reduces scattering of $^{32}O_2^-$. The compounds NF_3 and CF_4, which are known to cause mass interferences at m/e 33 ($^{17}O^{16}O$) or otherwise interfere with analysis, were monitored during each analysis by scanning m/e 52 (NF_2^+) and 69 (CF_3^+) [11].

Delta values are reported in the linearized form [12,13]:

$$\delta^{17}O' = 1000 \ln\left(\frac{^{17}R_{sa}}{^{17}R_{SMOW}}\right);$$

$$\delta^{18}O' = 1000 \ln\left(\frac{^{18}R_{sa}}{^{18}R_{SMOW}}\right)$$

with $^{18}R = {}^{18}O/^{16}O$ and $^{17}R = {}^{17}O/^{16}O$ for samples (sa) and Standard Mean Ocean Water (SMOW). The advantage of the linear δ' definition over the classic δ term $(^{x}R_{sa}/^{x}R_{ref}-1)$ is that mass-dependent fractionation follows straight lines in three-

isotope space (δ'–δ' plot). The deviation from the TFL can then defined in a linear form:

$$\Delta^{17}O' = \delta^{17}O' - 0.5305\delta^{18}O'$$

where 0.5305 refers to the slope β of the equilib-

Table 1
Laser oxygen isotope data of HED meteorites

Meteorite	Rock type	Sample type	$\delta^{18}O'$	$\delta^{17}O'$	$\Delta^{17}O' \pm 2SE$
Howardites					
Kapoeta	pm	p	3.542	1.652	-0.227 ± 0.020
Pavlovka	pm	f	3.507	1.631	-0.229 ± 0.018
Melrose	pm	p	3.905	1.829	-0.243 ± 0.019
Melrose	pm	p	4.295	2.048	-0.230 ± 0.022
Hughes	pm	f	3.670	1.717	-0.230 ± 0.018
Muckera	pm	f	3.765	1.752	-0.245 ± 0.031
Le Teilleul	pm	p	3.747	1.770	-0.217 ± 0.019
Eucrites					
Pasamonte	pm	p	3.744	1.809	-0.177 ± 0.017
Pasamonte	pm	p	3.694	1.769	-0.191 ± 0.015
ALHA76005	pm	p	3.759	1.755	-0.239 ± 0.022
ALHA78132	pm	p	3.593	1.712	-0.194 ± 0.020
DAG-391	pm	p	3.279	1.523	-0.216 ± 0.017
DAG-480	pm	p	3.685	1.731	-0.224 ± 0.018
Bouvante	m	p	3.521	1.634	-0.234 ± 0.024
Nuevo Laredo	m	p	3.577	1.673	-0.224 ± 0.026
Sioux County	m	p	3.628	1.712	-0.213 ± 0.015
Dhofar-182	m	f	3.229	1.488	-0.224 ± 0.016
Juvinas	m	p	3.562	1.675	-0.214 ± 0.017
Juvinas	m	p	3.577	1.688	-0.210 ± 0.014
Bereba	m	p	3.653	1.715	-0.223 ± 0.011
Cachari-I	m	p	4.480	2.147	-0.230 ± 0.014
Cachari-I	m	p	4.224	2.027	-0.214 ± 0.015
Millbillillie	m	f	3.517	1.639	-0.227 ± 0.023
Stannern	m	f	3.901	1.859	-0.210 ± 0.013
Stannern	m	f	3.493	1.653	-0.200 ± 0.022
HH 262	unbr.	f	3.543	1.662	-0.217 ± 0.016
Chervony Kut	m, unbr.	f	3.560	1.679	-0.209 ± 0.023
Caldera	m, unbr.	f,px	3.331	1.578	-0.189 ± 0.018
Ibitira	m, unbr.	p	3.720	1.903	-0.070 ± 0.019
Ibitira	m, unbr.	p	3.590	1.848	-0.057 ± 0.019
Serra de Magé	c, unbr.	p	3.111	1.417	-0.233 ± 0.019
Moore County	c, unbr.	p	3.747	1.763	-0.224 ± 0.016
Binda	pm, c	f	3.365	1.565	-0.220 ± 0.015
Moama	c, unbr.	f	3.473	1.648	-0.195 ± 0.021
Binola	c	f	3.907	1.848	-0.225 ± 0.012
DAG-443	c	p	3.738	1.765	-0.218 ± 0.015
Diogenites					
Tatahouine	m, unbr.	p	3.500	1.634	-0.223 ± 0.017
Johnstown UB	m	p	3.331	1.534	-0.233 ± 0.016
Johnstown B	m	p	3.473	1.624	-0.219 ± 0.014
Bilanga	m	f	3.677	1.730	-0.220 ± 0.021

Delta values are given in per mil. 2SE = 2 sigma standard error. DAG = Dar al Gani, HH = Hammadah al Hamra, Dhofar = Jiddat al Harasis, Oman; pm = polymict, m = monomict, c = cumulate, unbr. = unbrecciated; p = powder, f = fragments, px = pyroxene.

rium fractionation line in δ'–δ' space calculated from:

$$\beta = \frac{\left(\dfrac{1}{m_1} - \dfrac{1}{m_2}\right)}{\left(\dfrac{1}{m_1} - \dfrac{1}{m_3}\right)}$$

where m_1 is the atomic mass of ^{16}O (15.99491461), m_2 is the atomic mass of ^{17}O (16.999131), and m_3 is the atomic mass of ^{18}O (17.99916). The β value for equilibrium fractionation has been chosen because it is identical with the β value of 0.5288 ± 0.0031 (95% confidence limits) calculated from terrestrial mineral analyses.

The $\delta^{18}O'$ and $\Delta^{17}O'$ values of the reference oxygen have been calibrated to the SMOW scale using UWG-2, a garnet standard from the University of Wisconsin [14]. UWG-2 was also analyzed together with the HEDs. Eight analyses (Fig. 2) average at $\Delta^{17}O' = 0.000 \pm 0.010‰$ (2σ). Duplicate measurements of standards and samples reproduced within $< 0.015‰$.

3. Results

The $\Delta^{17}O'$ values of six howardites, 24 eucrites, and four diogenites range from -0.245 to $-0.057‰$ (Table 1). HEDs without Ibitira fall
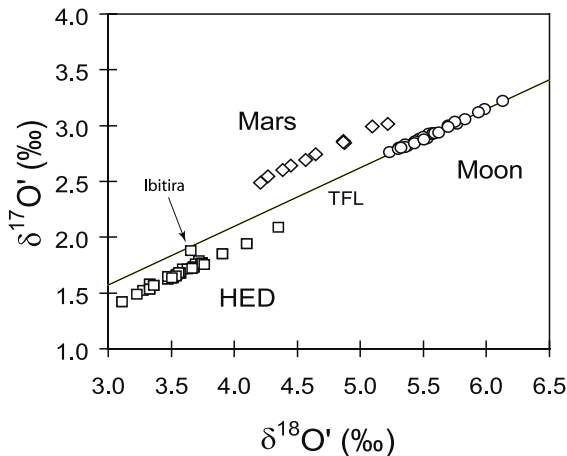

Fig. 1. Three-isotope diagram showing howardites, eucrites and diogenites analyzed in this study, lunar rocks [33], and Martian samples [34]. Bold line shows the TFL.
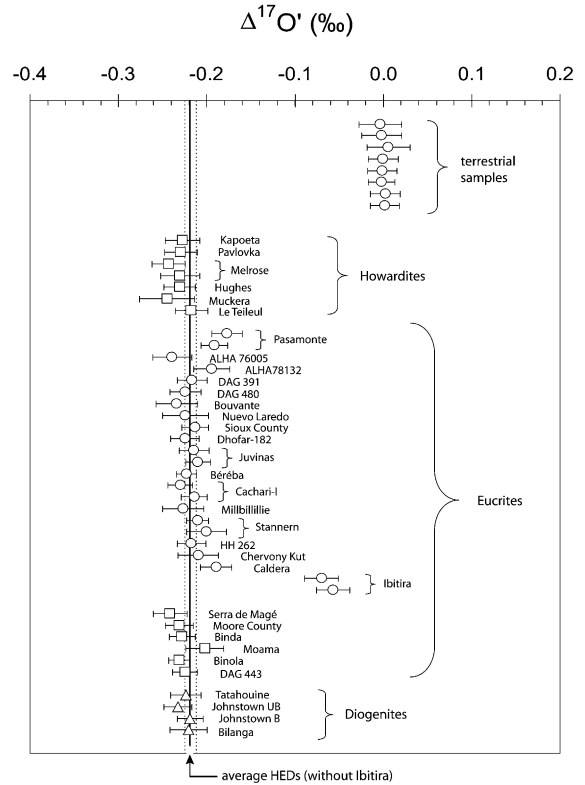

Fig. 2. $\Delta^{17}O$ values of six howardites (squares), 18 ordinary (circles) and six cumulate eucrites (squares), four diogenites (triangles) and eight measurements of a terrestrial garnet standard analyzed in this study. $\Delta^{17}O'$ gives displacement from the TFL defined as $\Delta^{17}O' = \delta^{17}O' - 0.5305\delta^{18}O'$. Also plotted is the average of the diogenites (bold line) and one standard deviation (dotted lines). Bars show 2σ standard errors.

along a mass-dependent fractionation line that lies at $-0.219 \pm 0.002‰$ (2σ standard error mean) relative to the TFL whereas Ibitira falls $0.064‰$ below the TFL (Fig. 1). The ordinary eucrites Caldera, Pasamonte, and ALHA78132 are different on the basis of the error (95% confidence) of individual $\Delta^{17}O'$ analyses (Fig. 2). Ten of these meteorites have been analyzed previously using a less precise method. The $\Delta^{17}O'$ values of all of the whole rock analyses are in excellent agreement (within $\pm 0.15‰$) with the exception of Ibitira [4]. However, previous mineral analyses of Ibitira agree with the result reported here [5].

The reproducibility of laser $\delta^{18}O'$ measurements is typically better than ± 0.2‰, as demonstrated by duplicate analyses (Table 1). The $\delta^{18}O'$ of diogenites, mainly orthopyroxene, varies between 3.3 and 3.7‰ whereas most eucrites range from 3.3 to 3.9‰ excluding the basaltic eucrite Cachari. The larger $\delta^{18}O'$ variation among cumulate and basaltic eucrites compared to diogenites may reflect different proportions of feldspar and pyroxene. A $\delta^{18}O' = 4.3$‰ of Cachari is consistent with a large proportion of feldspar. The reason for the low $\delta^{18}O'$ of the cumulate eucrite Serra de Magé is unknown. However, it has been noted that this meteorite has a chemical composition very similar to howardites. It is possible that Serra de Magé formed from a howardite-type regolith during an impact event and might represent a secondary cumulate [27]. The latter would be consistent with a slight enrichment in ^{16}O in three-isotope space. Overall the small range of $\delta^{18}O'$ values for eucrites and diogenites is consistent with a common magmatic history of the studied meteorites.

4. Discussion

4.1. The basis for a single HED parent body

The oxygen isotope data provide evidence that most meteorites are derived from a common, well-mixed pool. The eucrites (without Ibitira, Pasamonte, Caldera, and ALHA78132) and diogenites average $\Delta^{17}O' = -0.219 \pm 0.004$‰ and $\Delta^{17}O' = -0.224 \pm 0.006$‰ (2σ mean error) respectively and are therefore indistinguishable. Therefore, there is no evidence that eucrites and diogenites are from systematically distinct parent bodies or reservoirs. Some authors have suggested that cumulate and basaltic eucrites are derived from different parent bodies based on differences in Sr isotope initial ratios and petrological evidence [15–17]. Such a model is not supported by oxygen isotopes. In fact, the oxygen isotopes provide evidence that the petrogenesis of most orthopyroxene-rich diogenites and cumulate and basaltic eucrites is related, i.e. that they were derived from a single parent body.

However, whether this 'oxygen pool' that is sampled by most HED meteorites is representative of an entire parent body is now unclear because there are clearly resolvable differences for several samples. These deviations could reflect intrinsic heterogeneities in the HED parent body because of incomplete mixing at an early stage. Or, they could reflect incomplete admixing of late stage impacting material. Alternatively, it is conceivable that there was more than one parent body. In the following sections we will discuss this evidence and the most likely interpretations of the oxygen isotope data in more detail.

4.2. Evidence for a carbonaceous chondrite component in howardites

Howardites are polymict regolith breccias consisting mainly of mixtures of eucrites and diogenites. A minor chondritic component is supported by the presence of carbonaceous chondrite xenoliths in Kapoeta [18], as is also found in the polymict eucrite Pasamonte [19], and by concentrations of trace elements in howardites [20]. Chou et al. [20] have estimated some 2–3% of CM material in howardites, based on siderophile element abundances (Ni, Ir, etc.). The average $\Delta^{17}O' = -0.232 \pm 0.007$‰ of howardites is slightly enriched in ^{16}O relative to eucrites ($\Delta^{17}O' = -0.215 \pm 0.006$‰). When the anomalous eucrites Pasamonte, Caldera, and ALHA78132 are not considered the difference is even smaller ($\Delta^{17}O' = -0.219 \pm 0.004$‰) but still resolvable. The very small shift in ^{16}O of howardites is consistent with minor addition of carbonaceous chondrite material. However, the difference is small and errors on single $\Delta^{17}O'$ analyses (95% confidence) overlap with a mass-dependent fractionation line at -0.219‰ relative to the TFL. Therefore, admixed chondritic material is not yet detectable with oxygen isotopes in any single howardite sample analyzed in this study. Although a very slightly ^{16}O-enriched $\Delta^{17}O'$ average is plausible and basically confirms a chondritic component in howardites, our data limit a CM contribution to a maximum of 1% (see also Fig. 3). The discrepancy with the 2–3% CM material derived from trace element estimates reflects either a het-
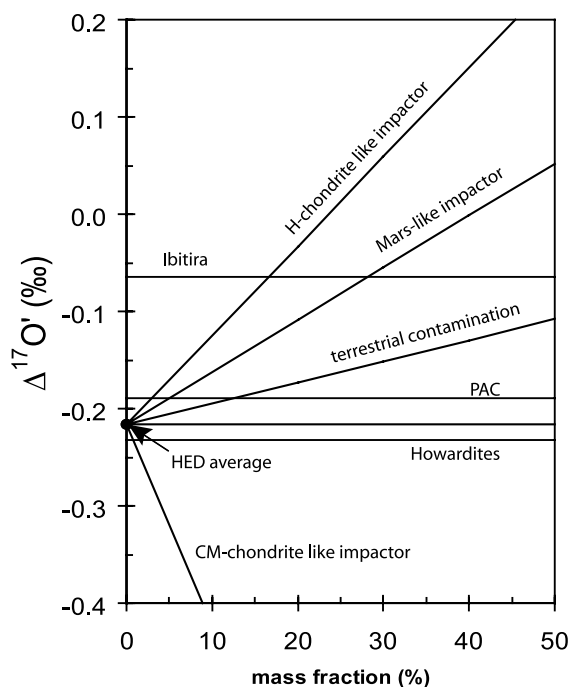
Fig. 3. The $\Delta^{17}O'$ average of the HED main group falls −0.219‰ below the TFL (black circle). On average Pasamonte, ALHA78132, and Caldera (PAC) fall −0.189‰ below the TFL and Ibitira −0.064‰. Terrestrial alteration would require replacement of >10% of the oxygen in main group HEDs to explain the PAC shift and more than 50% is required to produce the composition of Ibitira. Also shown are the effects of mixing in Mars-like, H-chondrite-like, and CM-chondrite-like material from putative impactors.

erogeneous distribution of chondritic material in howardites or that the elevated Ni and Ir abundances are not only derived from CM chondrites. The oxygen isotope data provide evidence of a late material flux that is ^{16}O-enriched, consistent with a bombardment by carbonaceous chondrites or differentiated objects formed from carbonaceous chondrites.

4.3. Origin of the ^{16}O depletion in selected eucrites

Although most of the eucrites fall along a mass-dependent fractionation line displaced −0.219‰ from the TFL (Fig. 1), the basaltic eucrites Ibi-

tira, Pasamonte, ALHA78132, and Caldera are significantly different (95% confidence). Any terrestrial alteration process would need to replace a minimum of 10% of the oxygen atoms to generate these differences from the HED average; more than 50% in the case of Ibitira (Fig. 3). For the whole rock powders of Ibitira, Pasamonte, and ALHA78132 weathering is not supported by other data. Although an exchange of 10% oxygen could explain the $\Delta^{17}O'$ value, such an intense alteration would also have shifted the $\delta^{18}O$ value. This is not observed (Table 1). Oxygen isotopes of Caldera have been measured on a clean pyroxene fragment. Therefore, weathering is not a viable process to explain ^{16}O depletion of Ibitira, Pasamonte, Caldera, and ALHA78132.

If one considers the $\Delta^{17}O$ to be a parent body 'fingerprint' [4] these meteorites could come from an asteroid that is distinct from the main group parent body. One would then expect differences in chemical compositions and these should be largest between the most distinct eucrite, Ibitira, and the main group eucrites. However, unlike NWA011 [10] the difference in oxygen isotopes of Ibitira and other eucrites is relatively small indicating only small differences in the source material. There is also no systematic difference in highly siderophile elements between Ibitira, Pasamonte, ALHA78132, Caldera and other eucrites [21]. There are also no source differences indicated by equally incompatible element ratios like K/U or Rb/Ba for Pasamonte, ALHA78132, and Caldera. These chemical 'fingerprints' are not very effective except for diagnosing large differences in components. In this respect it is interesting that only Ibitira, with its very distinctive oxygen isotope composition, also has distinctively low K/U and is anomalous in a TiO_2–Mg# diagram. It does not fit the Nuevo Laredo or the Stannern trends. Nor is it a member of the main group [1] indicating that magmatic differentiation of Ibitira was distinct from other basaltic eucrites. In particular for Ibitira an origin from a different parent body cannot be excluded. However, there are many chemical and isotopic similarities between Ibitira and other eucrites (e.g. fig. 1.2.8.2 in [22]) such that a distinct parent body origin for Ibitira is not without difficulty.

Another possibility is that the distinct $\Delta^{17}O'$ values of Pasamonte, ALHA78132, and Caldera originate from admixed impactor materials. These meteorites have relatively young isotopic ages suggesting resetting by impacts. Not only are the $^{39}Ar/^{40}Ar$ ages for Caldera relatively young, the $^{147}Sm–^{143}Nd$ isotope data for Pasamonte and Caldera clearly fall off the bulk rock isochron defined by other eucrites [23]. In contrast to howardites none of the ^{16}O-enriched carbonaceous chondrites groups could produce the observed oxygen isotope difference. Between 1 and 3% of ordinary chondrite-like material mixed into Pasamonte from an impactor could explain the difference, however (Fig. 3). This cannot be simple mechanical admixing of chondritic material because a minimum of 1% admixed ordinary chondrites would produce Ni and Ir concentrations of about 100 µg/g Ni and 5 ng/g Ir. This is inconsistent with reported Ni and Ir abundances for Pasamonte (12 µg/g Ni and 0.62 ng/g Ir [21]) and ALHA78132 (16 µg/g Ni and 0.87 ng/g Ir [24]). Furthermore, the oxygen isotope compositions for Caldera were measured on a clean pyroxene fragment providing evidence that the oxygen isotopic composition is inherited from the magma. Therefore, any impact model would require magmatic separation of Ni, Ir and other siderophile elements unless the putative impactors were achondrites.

These problems are amplified further when attempting to explain the oxygen isotopic composition of Ibitira. Ibitira has a distinctively low K/U ratio and is anomalous in a TiO_2–Mg# diagram [1]. However, an impact origin cannot explain the oxygen isotope composition of Ibitira with any of the known meteorite groups because even a putative impactor with an oxygen isotope composition of H-chondrites would require $> 15\%$ admixed material to generate the large deviation of Ibitira from the mass-dependent fractionation line of HEDs in a three-isotope plot (Fig. 3). An impact origin would only be possible if the admixed impactor was from a thus far unknown meteorite population, with oxygen isotopic compositions that are very different from those in eucrites, so that the fraction of foreign component required was much lower. Although the latter cannot be

excluded such a model has the disadvantage of being untestable.

A third possibility is that the HED parent body is heterogeneous in oxygen isotopes. This might explain why no differences in highly siderophile elements between Ibitira and other eucrites exist [21]. Ibitira is an unbrecciated basaltic eucrite with vesicular texture [25]. The vesicles indicate high volatile content of the magma and rapid cooling a few meters below the surface of the parent body [26]. The high volatile content may indicate an incompletely degassed source.

Distinctively low ratios of equally incompatible element ratios such as K/U or Rb/Ba can be explained with small source differences between Ibitira and other eucrites or might be due to loss of volatile elements during crystallization at the surface of the Ibitira parent body. Evaporation of volatile elements is consistent with distinct potassium isotopes of Ibitira [28]. Although the fractionation of potassium isotopes cannot be explained by a Rayleigh process and, therefore, did not happen in vacuum, other mechanisms such as evaporation under high gas pressure are possibly feasible [29]. Perhaps Ibitira crystallized from a lava flow before the solar nebula cleared. In fact a $^{53}Mn–^{53}Cr$ mineral isochron yields an age of $4557^{+2}/_{-4}$ million years [27] providing evidence that last equilibration of Ibitira was within < 5 million years of the formation of Juvinas. An early formation of Ibitira from a volatile-rich source may explain why magmatic differentiation of Ibitira was distinct from other basaltic eucrites, i.e. it is anomalous in a TiO_2–Mg# diagram [1].

The other anomalous eucrites Caldera, Pasamonte, and ALHA78132 might be derived from a distinct ^{16}O-depleted source within the HED parent body, although in detail their petrogenesis must have been different. From $^{147}Sm–^{143}Nd$, $^{146}Sm–^{142}Nd$, and $^{53}Mn–^{53}Cr$ chronometers isotopic closing for Caldera was estimated to have taken place at 4537 ± 12 million years ago [32]. Minerals have equilibrated chromium isotopes at $\varepsilon(53) = +1.12$. This is significantly higher than chromium isotope initials of Chervony Kut ($\varepsilon(53) = +0.49$) and Juvinas ($\varepsilon(53) = 0.56$). Therefore it has been suggested that the young age may

represent either a cooling age or Caldera crystallized from an impact melt that equilibrated chromium isotopes [27]. Very radiogenic chromium in the bulk rock is difficult to explain by impact melting alone. Caldera may have separated early from the mantle of the HED parent body, during the lifetime of ^{53}Mn, and either a long-lasting high-temperature metamorphism or a large impact event caused late equilibration. The former is consistent with the coarse grain size (typically a few mm) of Caldera and the fact that no vesicles have been found, unlike for Ibitira. Therefore, the distinct ^{16}O-depleted oxygen isotopes might also reflect early heterogeneity within the HED parent body.

For Pasamonte and ALHA78132 chromium isotopes are not available. However, a ^{207}Pb–^{206}Pb age of 4530 ± 30 and a ^{147}Sm–^{143}Nd internal isochron age of 4580 ± 12 million years for Pasamonte are among the oldest ages measured for eucrites [35]. It might therefore well be that the Pasamonte data are best explained by some primary oxygen isotope heterogeneity of the HED parent body, rather than a late impact.

Little is known for ALHA78132 but high ^{182}W/^{184}W indicates early separation of metal and silicates at 3.8 ± 1.2 [36,37] million years after the start of the solar system. If the shift in Δ^{17}O′ reflects source heterogeneity then this meteorite provides evidence that metal segregation took place without large-scale mixing and homogenization of the HED parent body.

4.4. Implications for the differentiation of the HED parent body

There is no consensus on the petrogenesis of eucrites. The oxygen isotope data allow one to draw some conclusions assuming that all of the HED samples analyzed came from a single parent body. Stolper [1] presented a model for eucrite petrogenesis in which basaltic eucrites represent primary partial melts of an undifferentiated parent body. In this model the parent body underwent minimal heating and only localized melting occurred. This model is especially attractive because ^{53}Mn–^{53}Cr and ^{182}Hf–^{182}W data indicate a very early formation of the HED parent body less

than 5 million years after CAI formation [37]. If the HED parent body was never completely homogenized some primary oxygen isotope heterogeneity should be found among most eucrites. Others have proposed that the HED mantle underwent a global magma ocean stage [3]. Such a magma ocean would help to explain why extremely early basaltic eucrites are derived from a parent body that appears to have been completely homogeneous in terms of oxygen isotopes within a few million years of the start of the solar system. However, such a model is in conflict with the oxygen isotope composition of Ibitira, Caldera, Pasamonte, and ALHA78132.

Gosh and McSween [30] suggested a model for the evolution of Vesta which assumes partial melting of the silicate mantle and low temperatures for near-surface layers. The thickness of an outer unaltered layer decreases with increasing degree of melting and, for 25% melting, the outer 10 km of the asteroid never reached melting temperatures. Such outer layers could have retained some isotopic heterogeneity. In contrast to the global magma ocean scenario [3] this model predicts mixing and perfect homogenization of the interior but also allows for some oxygen isotope heterogeneity in an outer layer of the HED parent body. In an early stage a metallic core is separated followed by enhanced heating of the silicate mantle mainly by radioactive decay of ^{26}Al. The temperature increases in the silicate portion because of the increased abundance of ^{26}Al. This will melt the lower part and reduce the thickness of the outer unmelted, isotopically heterogeneous layer. The lava flow from which Ibitira formed might have been derived from differentiated but still not well-mixed volatile-rich material. More lava flows might have reached the surface of the HED parent body which buried and metamorphosed the Ibitira lava flow [27]. The last metamorphic event on Ibitira has been dated at 4495 ± 15 million years ago [31]. This is among the oldest ^{39}Ar/^{40}Ar ages measured for a non-cumulate eucrite. At least since that time Ibitira has been part of a 'cold' crust and, therefore, must have escaped the catastrophic bombardment between ~ 4.1 and 3.5 billion years ago.

Caldera may have had a similar history as Ibi-

tira but has been metamorphosed at greater depth. This would explain the young age of Caldera. Pasamonte and ALHA78132 are both considered as polymict eucrites [19], i.e. they may have been part of the regolith breccia. These meteorites must have been part of the outermost crust to become part of the regolith. It is also clear that Pasamonte crystallized very early as suggested by Sm–Nd ages. Therefore it is possible that these meteorites tapped reservoirs with slightly different oxygen isotopes. However, in the case of regolith breccias, admixed impactor material cannot be excluded. Howardites and also Serra de Magé indicate late impactors that had carbonaceous chondrite compositions and these would shift oxygen isotopes in the opposite direction.

The Earth and Mars are both homogeneous in oxygen isotopes but this is because of protracted histories of extensive convective mixing. To achieve this in a planetesimal in the first few million years of the solar system implies very rapid heating and overturn given the heterogeneity exhibited by the accreted materials. Although homogenization has been very efficient within the interior of the HED parent body obviously some heterogeneity has survived in an outer layer. In the model of Gosh and McSween [30] a crust may have formed by extrusion of basaltic melts at the surface. Therefore it also explains why no anorthositic crust has been found on Vesta and may be a much better model for the formation of early crust on Earth than the Moon.

Acknowledgements

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