Meteoritics & Planetary Science 40, Nr 5, 665–677 (2005)
Abstract available online at http://meteoritics.org

Ibitira: A basaltic achondrite from a distinct parent asteroid and implications for the Dawn mission

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(Received 13 October 2004; revision accepted 30 March 2005)

Abstract–I have done a detailed petrologic study of Ibitira, a meteorite that has been classified as a basaltic eucrite since 1957. The mean Fe/Mn ratio of pyroxenes in Ibitira with <10 mole% wollastonite component is 36.4 ± 0.4; this value is well resolved from those of similar pyroxenes in five basaltic eucrites studied for comparison, which range from 31.2 to 32.2. Data for the latter five eucrites completely overlap. Ibitira pyroxenes have lower Fe/Mg than the basaltic eucrite pyroxenes; thus, the higher Fe/Mn ratio does not reflect a simple difference in oxidation state. Ibitira also has an oxygen isotopic composition, alkali element contents, and a Ti/Hf ratio that distinguish it from basaltic eucrites. These differences support derivation from a distinct parent asteroid. Thus, Ibitira is the first recognized representative of the fifth known asteroidal basaltic crust, the others being the HED, mesosiderite, angrite, and NWA 011 parent asteroids. 4 Vesta is generally assumed to be the HED parent asteroid. The Dawn mission will orbit 4 Vesta and will perform detailed mapping and mineralogical, compositional, and geophysical studies of the asteroid. Ibitira is only subtly different from eucritic basalts. A challenge for the Dawn mission will be to distinguish different basalt types on the surface and to attempt to determine whether 4 Vesta is indeed the HED parent asteroid.

INTRODUCTION

Eucrites are pigeonite-plagioclase basalts that are grouped with diogenites (coarse-grained orthopyroxenites) and howardites (polymict breccias of basalts, gabbros, and orthopyroxenites) into the HED clan of achondrites. These compose the largest suite of crustal rocks available from a differentiated asteroid, often equated with 4 Vesta (Drake 2001). Ibitira was recognized as a basaltic eucrite soon after its fall (Menezes 1957). Pristine mafic clasts from mesosiderites are virtually indistinguishable from HEDs, but because of their very different post-crust-formation history, mesosiderites likely were formed on a different parent asteroid (Mittlefehldt et al. 1998). The angrite group (olivine-diopside-anorthite basalts) is a much smaller suite, with compositional characteristics demonstrating a distinct formational history and parent asteroid (Mittlefehldt et al. 1998). Northwest Africa (NWA) 011 is a pigeonite-augite-plagioclase basalt; the sole representative of a fourth, differentiated asteroid crust (Yamaguchi et al. 2002). Basaltic achondrites are manifestations of one or more early, intense heat sources that were capable of rapidly bringing asteroid-sized bodies to igneous temperatures. Studies of these materials provide evidence on the nature of the early heat source(s) and the igneous evolution of their parent bodies.

This study was prompted by recent high precision oxygen-isotope data on a suite of HED meteorites (Wiechert et al. 2004), which showed that Ibitira deviated from a mass-dependent fractionation line defined by other HEDs (Fig. 1a). HED meteorites display a very restricted range in $\Delta^{17}O'$ (terminology of Wiechert et al. 2004), which indicates derivation from a homogeneous oxygen reservoir subject only to mass-dependent isotopic fractionation (Fig. 1b). In contrast, replicate analyses of Ibitira were displaced from other HEDs by roughly 16 times the 1σ analytical uncertainty (Wiechert et al. 2004). To further investigate the relationship of Ibitira to HEDs, I have done electron microprobe analyses of phases in it and representative basaltic eucrites. Here I report mineral compositional data and discuss literature bulk rock compositional data for Ibitira, nominally classified as a eucrite, which support derivation of this basaltic achondrite from a parent asteroid distinct from that of the HED clan.

SAMPLES AND ANALYTICAL METHODS

A thin section of Ibitira was made for this study by the

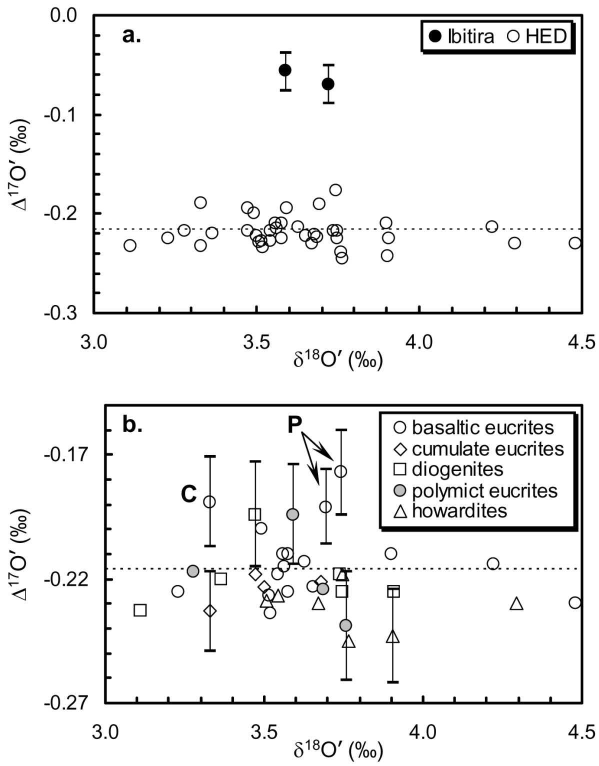

Fig. 1. Oxygen isotopic composition of Ibitira compared to HED meteorites (data from Wiechert et al. 2004). $\Delta^{17}O'$ is the deviation from the terrestrial mass-dependent fractionation line; mass-dependent fractionation on this diagram will yield horizontal data trends (Wiechert et al. 2004). The dashed line is the average $\Delta^{17}O'$ of the HED samples, exclusive of Ibitira and howardites (see text). a) Ibitira cannot be related to HED meteorites by simple chemical fractionation processes. The $\pm 2\sigma$ error bars for the Ibitira data are shown; these are typical of the analytical uncertainties (Wiechert et al. 2004). b) An expansion of the diagram showing only the HED data. Error bars ($\pm 2\sigma$) are shown for those samples that do not overlap the mean ratio. Two samples of Pasamonte (P) deviate from the mean ratio by 4σ on average, while Caldera (C) deviates by 3σ.

U. S. National Museum of Natural History (Smithsonian Institution). For comparative purposes, six basaltic eucrites were studied: Bates Nunataks (BTN) 00300, Elephant Moraine (EET) 90020, Graves Nunataks (GRA) 98098, Sioux County, Stannern, and Yamato (Y-) 793164. Until recently, Ibitira was considered to be unique as the only unbrecciated, metamorphosed basaltic eucrite (Gomes and Keil 1980; Steele and Smith 1976; Wilkening and Anders 1975). BTN 00300, EET 90020, and GRA 98098 are recently discovered unbrecciated and metamorphosed basaltic eucrites with petrologic similarities to Ibitira. Sioux County and Stannern are classic brecciated basaltic eucrites representative of the main group and Stannern trend (Stolper 1977). The Sioux County thin section was made from basalt clasts hand-picked from a sample obtained from the British Museum (Natural History). Y-793164 is classified as a eucrite, but has been paired with polymict eucrite Y-792769 based on texture, noble gas contents, and cosmic ray exposure and terrestrial residence ages (Miura et al. 1993; Takeda 1991). The sample studied here is believed to be a clast from the pairing group, and is a metamorphosed, ferroan basalt representative of evolved, Nuevo Laredo-trend basaltic eucrites (Mittlefehldt and Lindstrom 1993).

The electron microprobe analyses for all but Y-793164 were done using the Cameca SX100 electron microprobe at NASA Johnson Space Center. Y-793164 was analyzed using our previous microprobe, a Cameca CAMEBAX. Analytical conditions were 20 kV, 40 nA, 1 μm beam for pyroxene, chromite and ilmenite, and 15 kV, 20 nA, 1 μm beam for plagioclase. A key parameter evaluated in this study is the Fe/Mn ratio of pyroxene. For eucrite pyroxene analyses, the analytical conditions yield 1σ counting uncertainties on Fe/Mn of $\pm 0.76\%$. Total uncertainty on the precision can be estimated from the 1σ standard deviation of the mean of ratios, which is $\pm 1.2\%$. All meteorites were analyzed using the same analytical conditions, though at different times and over several years. The total uncertainty is a good measure to use when comparing the data sets to determine whether two populations are distinct.

RESULTS

Averages for low-Ca and high-Ca pyroxene for Ibitira are given in Table 1, average oxide analyses in Table 2, and average plagioclase analyses in Table 3. Figure 2a compares molar Fe/Mn for low-Ca pyroxene (<10 mole% wollastonite component) analyses between Ibitira and five basaltic eucrites, exclusive of ferroan Y-793164. The Ibitira data are well resolved from those of the five basaltic eucrites, while the data for the latter completely overlap. When all pyroxene analyses are considered irrespective of Ca content, the data distributions are still well resolved, with almost no overlap in ratios (Fig. 2b). Comparing Fe/Mn versus Fe/Mg for analyses with the lowest Ca contents, Ibitira has a higher Fe/Mn at lower Fe/Mg than the basaltic eucrites (Fig. 2c).

The Fe/Mg ratio of eucritic pyroxenes is inversely correlated with Ca content. To obtain comparable averages for Fig. 2c, only analyses within 2 mole% wollastonite component of the most Ca-poor analysis were averaged.

DISCUSSION

Ibitira has long been noted for having unusual characteristics. It contains abundant vesicles (Wilkening and Anders 1975), which are rare in HEDs (Mittlefehldt et al. 1998). It is unbrecciated with a fine-grained, hornfels texture (Steel and Smith 1976), which until recently was unique among HEDs. Plagioclase in Ibitira is unusually calcic, An_{95} (Steele and Smith 1976; Wilkening and Anders 1975) (Table 3), compared to plagioclases found in basaltic eucrites, $An_{75–93}$ (Mittlefehldt et al. 1998; Papike 1998). This is an

Table 1. The average analyses of representative pyroxenes for Ibitira.

	Pigeonite				Augite
Type	Host	Host	Lamella[b]	Lamella	host[c]
n[a]	8	10	3	10	13
SiO_2	48.9	48.9	49.0	48.4	49.0
TiO_2	0.40	0.59	1.10	0.94	1.10
Al_2O_3	0.35	0.44	1.54	1.08	1.36
Cr_2O_3	0.21	0.23	0.49	0.41	0.48
FeO	33.5	33.1	18.9	21.3	17.9
MnO	0.910	0.900	0.519	0.582	0.509
MgO	13.1	13.0	11.0	11.6	10.6
CaO	1.84	2.04	16.1	14.1	18.0
Sum	99.210	99.200	98.649	98.412	98.949
Molar					
Fe/Mn	36.3	36.3	35.9	36.1	34.7
Fe/Mg	1.43	1.43	0.96	1.03	0.95
mg#	41.1	41.2	50.9	49.3	51.4
wo	4.0	4.4	34.9	30.1	38.5
en	39.4	39.4	33.2	34.4	31.6
fs	56.6	56.2	32.0	35.5	29.9
Atoms per 6 oxygens					
Si	1.9618	1.9593	1.9234	1.9192	1.9201
Ti	0.0121	0.0178	0.0325	0.0280	0.0324
Al	0.0166	0.0208	0.0713	0.0505	0.0628
Cr	0.0067	0.0073	0.0152	0.0129	0.0149
Fe	1.1240	1.1092	0.6205	0.7063	0.5866
Mn	0.0309	0.0305	0.0173	0.0196	0.0169
Mg	0.7834	0.7765	0.6437	0.6857	0.6192
Ca	0.0791	0.0876	0.6772	0.5991	0.7558
Sum	4.0146	4.0090	4.0011	4.0213	4.0087

[a]Number of analyses averaged.
[b]Three most Ca-rich lamella analyses from three pigeonite hosts.
[c]Thirteen most Ca-rich analyses from four augite hosts.

expression of the low alkali element content of Ibitira compared to HED basalts (Stolper 1977). These atypical characteristics, coupled with the recent oxygen isotopic distinction (Wiechert et al. 2004), led me to question whether Ibitira was a basaltic eucrite sensu stricto.

Oxygen isotopic compositions are but one means to distinguish the heritage of planetary basalts; Fe/Mn ratios are also diagnostic (Papike 1998). Manganese is a moderately volatile element with a 50% condensation temperature roughly 150° lower than that of Fe; Mn also condenses in olivine (lithophile), whereas Fe condenses in metal (siderophile) (Lodders and Fegley 1998). Manganese was fractionated from Fe by nebular processes as a consequence; bulk chondrite Fe/Mn ratios vary by a factor of 2 (Lodders and Fegley 1998). Manganese is almost strictly divalent in chondritic materials, although Mn sulfides are present in the most reduced chondrites. Iron in chondrites can be in valence states of 0, 2+, and/or 3+, depending on oxygen fugacity, and Fe more readily forms sulfides. Thus, primitive bodies in the solar system had very different Fe/Mn ratios in their silicates as a consequence of volatility and oxidation state controls. Ferrous iron and Mn^{2+} are homologous cations; they have very similar ionic radii (78 versus 83 pm) (Lodders and Fegley 1998). Because of this, they are inefficiently fractionated in ultramafic-mafic igneous systems (Stolper 1977) and different parent bodies can maintain distinct Fe/Mn ratios of the silicate system through planetary differentiation processes (Papike 1998; Wänke et al. 1973). Thus, the non-metallic portions of parent bodies can have quite different Fe/Mn and this will be reflected in their basalts (Papike 1998).

In basaltic achondrites, pyroxene contains the bulk of the whole rock Fe and Mn. Among low-Ca pyroxene (<10 mole% wollastonite component) analyses, there is no overlap in Fe/Mn ratios between Ibitira and five representative basaltic eucrites (Fig. 2a) and almost no overlap when all analyses irrespective of Ca content are considered (Fig. 2b). The data from the five basaltic eucrites completely overlap (Figs. 2a and 2b). The higher Fe/Mn ratio for Ibitira could simply indicate a slightly higher oxidation state for this basalt, rather than a fundamental difference in its source or petrologic evolution. However, higher oxidation state would also result in higher Fe/Mg. Ibitira has lower molar Fe/Mg in its low-Ca pyroxenes (Fig. 2c) compared to those of the five basaltic eucrites studied here. Thus, the

Table 2. The average analyses of representative ilmenite and ulvöspinel grains (two each) for Ibitira.

	Ilmenite		Ulvöspinel	
n[a]	7	3	5	5
TiO_2	53.2	52.8	21.6	23.1
SiO_2	0.04	0.03	–	–
Cr_2O_3	0.19	0.66	20.8	19.0
Al_2O_3	0.02	0.02	4.35	3.78
V_2O_3	–	–	0.100	0.094
FeO	43.2	43.6	50.2	51.2
MnO	0.680	0.609	0.533	0.532
MgO	1.26	1.12	1.01	0.98
CaO	0.02	–	0.01	0.01
Sum	98.610	98.839	98.603	98.696
Molar				
Fe/Mn	62.7	70.7	93.0	95.0
mg#	4.94	4.38	3.46	3.30
cr#	–	–	76.2	77.1
Atoms per 3 oxygens (ilmenite) or 4 oxygens (spinel)				
Ti	1.0089	1.0015	0.5966	0.6386
Si	0.0010	0.0008	–	–
Cr	0.0038	0.0132	0.6040	0.5522
Al	0.0006	0.0006	0.1883	0.1638
V	–	–	0.0029	0.0028
Fe	0.9111	0.9197	1.5418	1.5740
Mn	0.0145	0.0130	0.0166	0.0166
Mg	0.0474	0.0421	0.0553	0.0537
Ca	0.0005	–	0.0004	0.0004
Sum	1.9878	1.9909	3.0059	3.0021

[a]Number of analyses averaged. A dash indicates "below detection limit" or "not calculated."

Table 3. The average analyses of three representative plagioclase grains for Ibitira.

n[a]	5	5	5
SiO_2	44.2	44.1	43.7
Al_2O_3	36.0	36.1	36.0
FeO	0.22	0.41	0.29
MgO	0.041	0.031	0.035
CaO	19.2	19.1	19.2
Na_2O	0.53	0.53	0.48
K_2O	0.048	0.046	0.043
Sum	100.239	100.317	99.748
mole%			
an	95.0	94.9	95.4
ab	4.7	4.8	4.3
or	0.3	0.3	0.3
Atoms per 8 oxygens			
Si	2.0391	2.0343	2.0277
Al	1.9576	1.9629	1.9689
Fe	0.0085	0.0158	0.0113
Mg	0.0028	0.0021	0.0024
Ca	0.9491	0.9441	0.9546
Na	0.0474	0.0474	0.0432
K	0.0028	0.0027	0.0025
Sum	5.0073	5.0093	5.0106

[a]Number of analyses averaged.

difference between Ibitira and basaltic eucrites is inconsistent with simple redox variations.

Other geochemical characteristics distinguish Ibitira from basaltic eucrites. Ibitira is anomalously depleted in alkali elements (Stolper 1977) and also is enriched in Ti compared to other incompatible refractory lithophile trace elements. Ibitira is well resolved from basaltic eucrites, angrites, NWA 011, and basalt clasts from mesosiderites on a plot of $(Ti/Hf)_{CI}$ versus $(Na/Ca)_{CI}$ (Fig. 3). On this diagram, NWA 011 is indistinguishable from basaltic eucrites, but it is very different in O isotopic composition and Fe/Mn (Yamaguchi et al. 2002). Angrites are well separated from basaltic eucrites in Na/Ca and have distinct Fe/Mn (Mittlefehldt et al. 1998) and O isotopic compositions (Franchi and Greenwood 2004). Curiously, Ibitira and angrites are indistinguishable in O isotopic composition (Franchi and Greenwood 2004), although they are distinct in Na/Ca and Fe/Mn. Primary basalt clasts from mesosiderites (Rubin and Mittlefehldt 1992) are not distinguishable from basaltic eucrites (Fig. 3).

There are two basic models for petrologic evolution of the HED parent asteroid: either basaltic eucrites represent residual melts from crystallization of a totally molten asteroid (Righter and Drake 1997; Ruzicka et al. 1997) or they are partial melts of a partially melted asteroid (Stolper 1977). In the former case, silicate material initially would have been well mixed, and oxygen isotopic, Fe/Mn, Ti/Hf, and Na/Ca ratios should be uniform. Crystallization of the molten asteroid will not alter the $\Delta^{17}O'$ of the melt, while Fe/Mn will slightly decrease during olivine crystallization and then slightly increase when pyroxene becomes the major crystallizing phase (Stolper 1977). Titanium and Hf are incompatible elements; Ti/Hf will decrease slightly with solidification, as Hf will be slightly more incompatible owing to its larger ionic radius (83 versus 60 pm) (Lodders and Fegley 1998). Ilmenite fractionation would drastically lower the Ti/Hf ratio, but ilmenite only forms late in eucrite crystallization, as indicated by textural studies (Mittlefehldt et al. 1998), and could not have affected bulk rock Ti/Hf ratios. The Na/Ca ratio will slightly increase with pyroxene and plagioclase crystallization. An equilibrium crystallization model for the HED parent asteroid calculates only a 50% increase in Na/Ca by 85% solidification (Righter and Drake 1997), while a fractional crystallization model calculates only 12% increase by 77% solidification (Ruzicka et al. 1997). The average Na/Ca ratio for basaltic eucrites is 2.5 times that of Ibitira. The differences in composition between Ibitira and basaltic eucrites (Figs. 1–3) are inconsistent with formation on a single, once molten body, and would indicate distinct parent-asteroid sources if this is the correct model for eucrite petrogenesis.

Wiechert et al. (2004) have argued that even for these

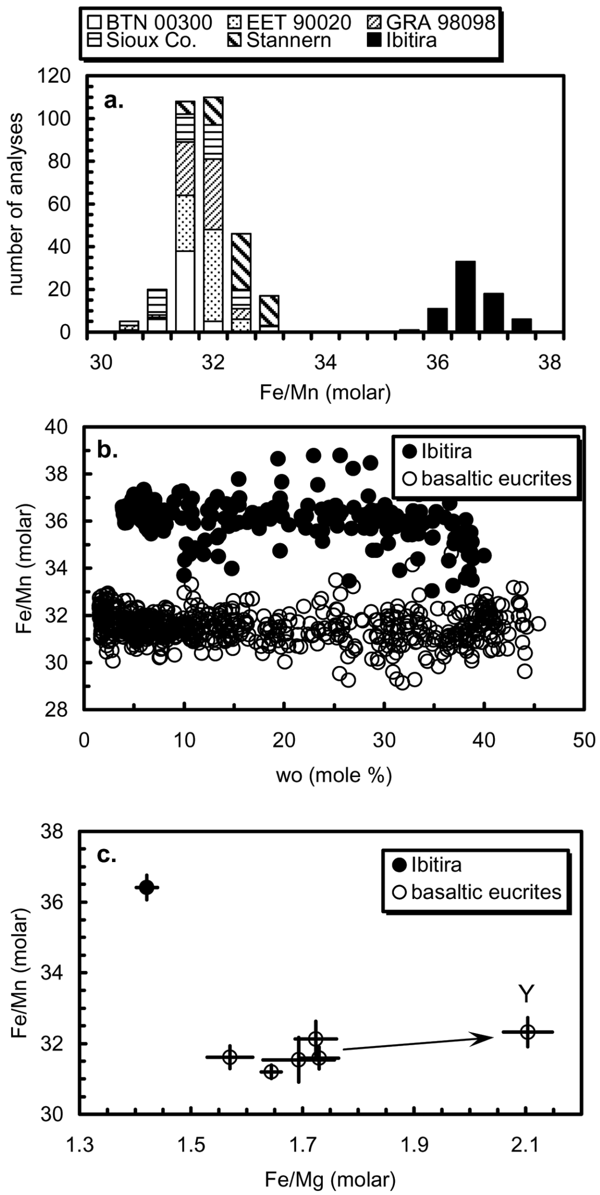

Fig. 2. Pyroxene compositional data for Ibitira compared to several basaltic eucrites. a) An Fe/Mn histogram of individual analyses with <10 mole% wollastonite component. Ibitira is completely resolved from the basaltic eucrites, while data for the latter completely overlap. b) Pyroxene compositional data for Ibitira compared to those for five basaltic eucrites. There is almost no overlap in molar Fe/Mn between Ibitira analyses and those of the basaltic eucrites, regardless of Ca content. The basaltic eucrite data completely overlap and individual samples are not distinguished. c) Fe/Mn versus Fe/Mg for Ibitira compared to basaltic eucrites, plus a ferroan residual basalt clast (Y) from Y-793164 (Mittlefehldt and Lindstrom 1993). The data are averages of individual analyses within 2 mole% wo of the most Ca-poor analysis. The error bars are 1σ standard deviations of the means. Igneous fractionation would yield a slightly sloped, nearly horizontal trend on this diagram (arrow), while Fe redox will result in a positive Fe/Mn-Fe/Mg correlation. Ibitira cannot be related to the basaltic eucrites by either mechanism.

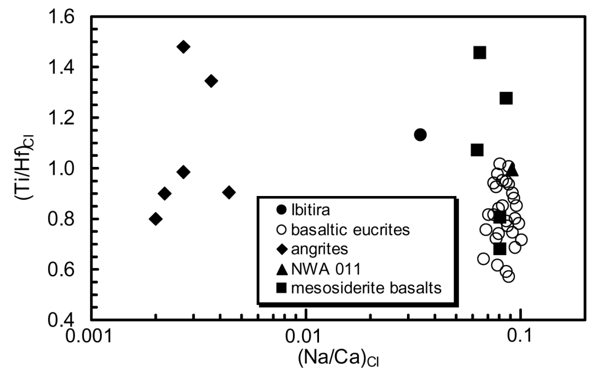

Fig. 3. CI-normalized Ti/Hf versus Na/Ca diagram comparing Ibitira to basaltic eucrites, angrites, NWA 011, and primary basaltic clasts from mesosiderites. Ibitira is distinct from any of these other asteroidal basalts. The data averages used in this figure and sources of the data are given in the Appendix (Tables A1 and A2).

crystallization scenarios, the parent asteroid would not have been totally molten. They note that the thermal modeling of Ghosh and McSween (1998) shows a cold thermal boundary layer at the surface of the molten asteroid, where temperatures are below the Fe-FeS eutectic temperatures for the outer 5–7 km. Wiechert et al. (2004) suggest that the O isotopic heterogeneity of the HED suite can be explained as arising from incomplete mixing of this thermal boundary layer with the molten interior. However, the thermal boundary layer will be much denser than the interior silicate melt both because it is colder and because it still contains the metallic fraction. It is implausible that this dense boundary layer would persist over a convecting molten interior; foundering and mixing with the interior seems inescapable. Regardless, Ibitira is a basalt and could not represent the outermost thermal boundary layer.

The case is not as clear if eucrites were formed by partial melting. In principle, a heterogeneous parent asteroid could produce a suite of basalts that differ in these compositional parameters. For example, ureilites are generally considered to be partial-melt residues and to come from a single parent asteroid (Mittlefehldt et al. 1998), yet they exhibit substantial ranges in oxygen isotopic composition (Clayton and Mayeda 1996) and molar Fe/Mn (Mittlefehldt et al. 1998). If individual basalt flows represent partial melts of limited regions of their parent asteroid that did not completely mix or equilibrate with other material during ascent and eruption, then isotopic and chemical heterogeneities could be partially preserved. Note that ureilites show a positive correlation between Fe/Mn and Fe/Mg that passes through the origin, consistent with redox control (Mittlefehldt et al. 1998). This contrasts with the difference between Ibitira and basaltic eucrites (Fig. 2c).

Wiechert et al. (2004) recognized that Ibitira could be from a distinct parent asteroid, but argued in favor of derivation from a heterogeneous HED parent asteroid. Based on Figs. 1–3, Ibitira would have to be the sole representative of a source region that produced basalts with distinct oxygen isotopic composition, slightly higher mg#, higher Fe/Mn, a depletion in alkali elements, and a higher Ti/Hf ratio. The simpler explanation is that Ibitira was derived from a distinct parent asteroid.

Support for this position comes from the cosmic ray exposure record of HEDs, which shows at least three significant age clusters, indicating separate impact events that liberated the majority of HED meteorites (Eugster and Michel 1995; Welten et al. 1997). The high precision oxygen isotopic data for HEDs cover most of the cosmic ray exposure age range, including the three age clusters.

There are two interpretations of the cosmic ray exposure age clusters. The first is that they represent three separate launch events from random regions of the parent asteroid (Eugster and Michel 1995; Welten et al. 1997). This interpretation implies that the "normal" oxygen isotopic reservoir is widespread and dominates on the HED parent asteroid. Ibitira is unlikely to have originated on the HED parent asteroid if this interpretation is correct.

The second interpretation is that the clusters date the breakup of multi-kilometer spalls from the parent asteroid (Migliorini et al. 1997). These spalls could have been derived from a single, basin-forming impact on the parent asteroid, thus representing one extensive region of the crust. The common interpretation is that these spalls were derived from the southern basin on 4 Vesta (Thomas et al. 1997) that covers roughly 15% of the surface. This would more easily allow for anomalous basalts like Ibitira to have existed on the HED parent asteroid; it could have been ejected from a distant region of 4 Vesta by a smaller impact.

Among the HED samples analyzed are several polymict breccias; these have oxygen isotopic compositions like those of diogenites, cumulate eucrites, and basaltic eucrites (Wiechert et al. 2004). Howardites are regolith samples of the HED asteroid. Regolith formation on asteroids involves widespread mixing over the surface (Housen et al. 1979). If oxygen isotopic heterogeneity of the magnitude demonstrated by Ibitira (16 times the 1σ analytical uncertainty) was common on the HED surface when regolith formation occurred, howardites ought to be notably more heterogeneous than HED monomict breccias. This is not observed (Wiechert et al. 2004). Actually, howardites are slightly enriched in ^{16}O compared to basaltic eucrites due to inclusion of a small amount of CM and CR chondrite debris (Wiechert et al. 2004; Zolensky et al. 1996) (Fig. 1b). Wiechert et al. (2004) noted that polymict eucrite Allan Hills (ALH) A78132 is depleted in ^{16}O compared to HEDs. However, paired polymict eucrite ALH A76005 is ^{16}O-enriched and the average Δ^{17}O' ratio for them is identical to the HED mean. Whether this reflects real isotopic heterogeneity of the meteorite should be addressed.

Wiechert et al. (2004) also found that two basaltic eucrites are depleted in ^{16}O relative to the HED mean. A single analysis of Caldera is discrepant in Δ^{17}O' by 0.027‰ (3σ deviation), while duplicate analyses of Pasamonte are displaced by an average of 0.032‰ (4σ deviation) (Fig. 1b). Caldera is a coarse-grained, unbrecciated basaltic eucrite (Boctor et al. 1994). Pasamonte is a basaltic eucrite that was only relatively recently recognized as having polymict character (Metzler et al. 1995). The data for these two eucrites suggest that oxygen isotopic heterogeneity in Δ^{17}O' on the order of 0.03‰ may exist on the HED parent body. Nevertheless, the relative isotopic uniformity of the howardites argues against Ibitira-like terranes being common on the HED parent body.

One could always posit that Ibitira is an impact melt from the HED parent asteroid and that its unique compositional characteristics relative to basaltic eucrites result from the impact process. The greater Δ^{17}O' of Ibitira compared to HEDs would then indicate substantial contamination by the impactor, which would have a much greater Δ^{17}O'. R chondrites have the highest known Δ^{17}O' (Weisberg et al. 1991); roughly 6% R chondrite contamination could explain the O isotopic composition of Ibitira. However, Ibitira has very low contents of the highly siderophile elements Re and Ir (2 and 3.9 pg/g, respectively) (Higuchi and Morgan 1975), precluding contamination by R chondrites, which have on average 43000 and 610000 pg/g, respectively (Lodders and Fegley 1998). Only an achondritic impactor could satisfy the tight siderophile elements constraints. Regardless, no textural characteristics of Ibitira suggest that it is an impact-melt and an origin by this process seems unlikely.

On balance, the simplest explanation for the oxygen isotopic, pyroxene composition, bulk composition, and cosmic ray exposure data for Ibitira and HEDs is that the former was derived from a distinct parent asteroid. By virtue of Ockham's razor, this is the more plausible explanation.

Meibom and Clark (1999) estimated the number of asteroids represented in the meteorite collection at about 135, with the largest fraction of these being represented by irons. Most irons are fragments of cores of differentiated asteroids (Mittlefehldt et al. 1998). Thus, basaltic crusts should have been common in some portion of the asteroid belt. Based on the arguments put forth above, five of these crusts have been sampled, that is, HEDs, mesosiderite silicates, angrites, NWA 011, and Ibitira. Of these, NWA 011 stands out as having a very different oxygen isotopic composition, similar to that of CR chondrites (Yamaguchi et al. 2002) and was likely derived from a region of the asteroid belt distant from the other four parent asteroids. The other four sampled crusts have very similar oxygen isotopic compositions, suggesting that their parent asteroids accreted material from a more limited region of the nebula. The angrites are quite different in Fe/Mn, Na/Ca, and oxidation state, however (Mittlefehldt et al. 1998).

With only one example available for study, detailed reconstruction of Ibitira's parent asteroid cannot be made.

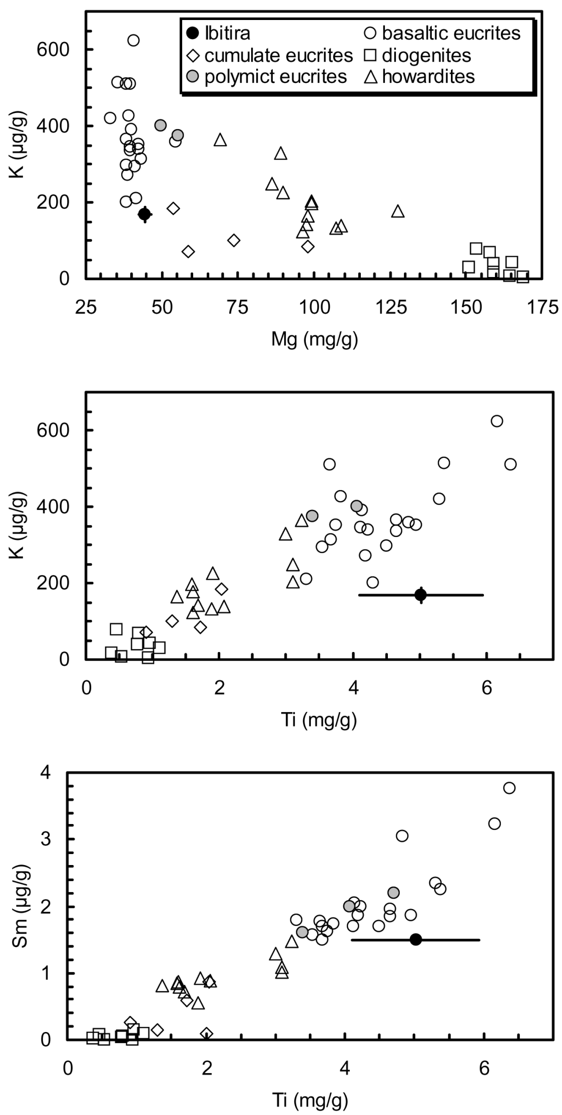

Fig. 4. K versus Mg, K versus Ti, and Sm versus Ti for average whole rock HED meteorites compared to Ibitira. Magnesium, K, Ti, and Sm are elements to be determined by the Dawn mission at 4 Vesta (Russell et al. 2004). Because Ibitira is depleted in alkali elements compared to HEDs (Stolper 1977), K may be particularly diagnostic for comparing basaltic achondrites with the vestan crust. The error bars shown for Ibitira represent the expected uncertainties for Dawn measurements at those concentrations and for the assumed mission plan (Russell et al. 2004). No error estimates for Sm were given. It will be challenging to distinguish Ibitira from some basaltic eucrites from vestan orbit.

Nevertheless, the differences between Ibitira and basaltic eucrites allow some basic inferences to be made. Ibitira has concentrations of highly incompatible refractory lithophile elements similar to those of basaltic eucrites: La 2.54 µg/g versus 2.56 µg/g for Juvinas, for example. Neither is depleted in Eu relative to Sm, indicating that plagioclase fractionation did not affect their compositions. Thus, to first order, Ibitira and Juvinas represent melts from similar stages of evolution of their respective parent asteroids. Ibitira has a more magnesian composition, as evidenced in its pyroxene (Fig. 2c) and bulk rock compositions (mg# 41.4 versus 40.5 for Juvinas), suggesting that its parent asteroid has a slightly higher mg#. The higher Fe/Mn coupled with lower Fe/Mg (Fig. 2c) suggests depletion in moderately volatile Mn, which is also indicated by the low alkali element contents of Ibitira (Fig. 3). More detailed comparisons will require identification of additional samples from the Ibitira parent asteroid; these may already exist in the collection of poorly characterized eucrites.

The discovery of small, V-type asteroids dynamically associated with 4 Vesta, the so-called vestoids, strengthened the case for identifying 4 Vesta as the HED parent asteroid (Binzel and Xu 1993). Some of these vestoids are near the 3:1 Kirkwood gap or ν_6 resonance that are potential escape hatches to near Earth orbits. Evidence is accumulating, however, that the vestoids may actually represent fragments from more than a single differentiated asteroid. Sykes and Vilas (2001) noted that those vestoids that are dynamically most distinct from 4 Vesta are difficult to reconcile as having originated as vestan ejecta with the current understanding of collisional evolution of the asteroid belt. There is also a distinction in the distribution of the 0.506 µm absorption feature attributed to Ca-rich pyroxene among the vestoids; those that are dynamically most closely linked to Vesta generally lack this feature, while those most distant from 4 Vesta more commonly have this feature (Sykes and Vilas 2001). These authors thus suggested that the vestoids may represent collisional fragments of two parent asteroids: 4 Vesta and a similar asteroid that has been destroyed. Florczak et al. (2002) noted that two of the three V-type asteroids they studied are dynamically far from 4 Vesta; they also noted that there are slight spectral differences between 4 Vesta and nearby vestoids on one hand and more distant V-type asteroids on the other. They also suggested that some V-type asteroids might be fragments of a different parent asteroid. Because differences between Ibitira and basaltic eucrites are small, their parent asteroids likely were formed within a limited region of the asteroid belt. This is consistent with the emerging astronomical evidence on vestoids, suggesting multiple differentiated asteroids in near 4 Vesta space.

The mesosiderite parent asteroid also ought to be within the same region of the asteroid belt by virtue of the very similar compositional characteristics of the basalt suites (Fig. 3). If the high metal content of mesosiderites is typical of the surface of their parent asteroid, it will have very different spectroscopic characteristics from the vestoids. Some S class asteroids of the Agnia (radius 14 km) and Merxia (radius 16 km) families have reflectance spectra consistent with mafic silicates, but with subdued absorption features suggestive of a high abundance of opaque material

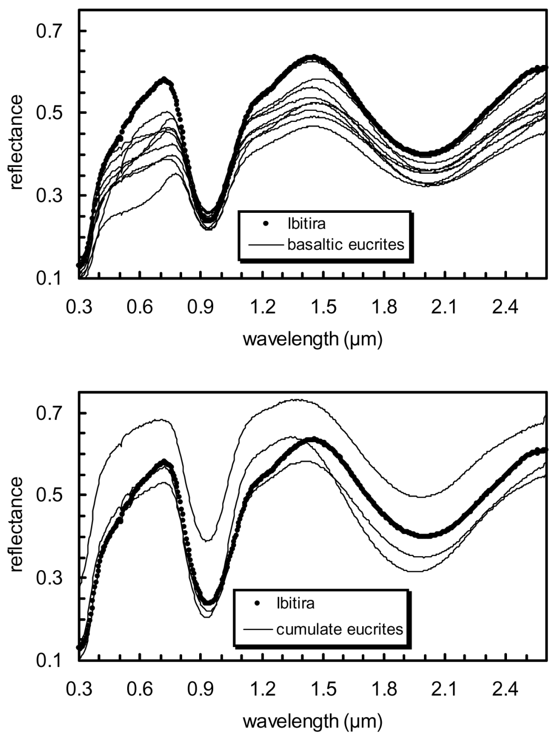

Fig. 5. A comparison of the reflectance spectrum of Ibitira with those of several basaltic and cumulate eucrites. If the basaltic eucrites shown are representative of the suite as a whole, then it may be possible to distinguish between them and Ibitira-like basalts on 4 Vesta. For example, none of the basaltic eucrites have a 0.9 μm pyroxene absorption feature as deep as shown by Ibitira. However, these spectra are for "ideal" samples, that is, carefully prepared in the laboratory from distinct rocks. The surface of 4 Vesta will be more complicated. The spectra were collected by T. Hiroi and are publicly available from the Brown University Keck/NASA Reflectance Laboratory (RELAB) (http://www.planetary.brown.edu/relab). A listing of the spectra used and a synopsis of analysis details are given in the Appendix (Table A3).

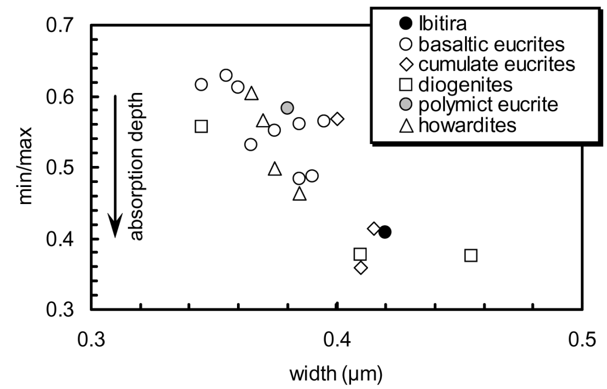

Fig. 6. Comparison of the strength of the 0.9 μm pyroxene absorption feature in RELAB spectra of Ibitira compared to HED meteorites. The width is the difference in wavelength between the shoulder in the spectrum on the long wavelength side of the absorption feature and the reflectance maximum on the short wavelength side. Min/max is a measure of the depth of the feature; the reflectance minimum near 0.9 μm/reflectance maximum in the 0.6–0.8 μm region.

(Sunshine et al. 2004). One candidate for this opaque material is metal, so these asteroids are therefore potential crust fragments of the mesosiderite parent asteroid (Sunshine et al. 2004).

The Dawn mission, scheduled for launch in June-July 2006, will orbit 4 Vesta for seven months starting in October 2011 (Russell et al. 2004). The data return will include full surface imagery, spectrometry mapping in visible and infrared bands, and abundances of H, O, Mg, Al, Si, K, Ca, Ti, Fe, Sm, Gd, Th, and U. Spectroscopic data on HED meteorites are being collected as "ground truth" for comparison with spacecraft acquired data; a vast body of compositional data exists for HEDs. The mineralogical and chemical distinctions between Ibitira and basaltic eucrites are subtle. This will pose a challenge for investigators attempting to distinguish geologic terranes or equate specific basaltic achondrites with the vestan crust, based on spacecraft data.

The low alkali element contents of Ibitira offer one opportunity to distinguish it from basaltic eucrites from 4 Vesta orbit. Ibitira has a lower K content than do basaltic eucrites (Stolper 1977). However, the K contents of the latter scatter more than do the Na contents (Mittlefehldt 1987) and distinguishing Ibitira-like basalts from HED-like basalts will be difficult based on K. Figure 4 shows K versus Mg and K versus Ti for Ibitira and HEDs. Ibitira lies at the low K end of the basaltic eucrite continuum and Ibitira-like terranes on 4 Vesta may simply appear to be K-poor basaltic eucrite-like terranes on 4 Vesta. Ibitira has a higher Ti content relative to other refractory incompatible elements compared to basaltic eucrites (Fig. 3), and stands out on K versus Ti and Sm versus Ti plots (Fig. 4). However, Ti measurement errors expected for the Dawn mission are substantial (Russell et al. 2004, no error estimates were given for Sm) and data from Ibitira-like terranes will overlap those from basaltic eucrite-like terranes (Fig. 4).

A reflectance spectrum of Ibitira determined at the Brown University Keck/NASA Reflectance Laboratory (RELAB) is distinct from those of most basaltic and cumulate eucrites determined under identical experimental conditions (Fig. 5). However, portions of individual eucrite spectra can closely match the Ibitira spectrum. Thus, Moore County (cumulate eucrite) is similar to Ibitira in the region of the 0.9 μm pyroxene absorption feature, while Cachari (basaltic eucrite) is a close match from ~0.81 to 1.74 μm. Binzel et al. (1997) showed that spectra of 4 Vesta (52 km/pixel resolution) have 0.9 μm pyroxene absorption features that display a range of depths and widths, which they used to demonstrate geological heterogeneity of the surface. Figure 6 is a plot of depth versus width of the 0.9 μm pyroxene absorption feature of RELAB spectra of Ibitira and several HEDs. Ibitira has a deeper and wider feature than do basaltic eucrites measured under identical conditions. However, some cumulate eucrites are similar to Ibitira in the shape of the 0.9 µm pyroxene absorption feature. (Some diogenites are similar as well, but the lack of a plagioclase absorption feature would allow them to be distinguished from Ibitira-like basalts.)

The discussion of spectra above was based on "ideal" spectra, that is, spectra taken under controlled conditions on carefully prepared samples of igneous lithologies. The vestan surface will not be so accommodating. The surface will be covered with regolith of mixed fragmental debris unsorted by size and space weathering will have altered the spectral properties. Combining chemical and spectroscopic data will allow inferences regarding the types of igneous materials in the vestan crust. Nevertheless, it will be a challenge to distinguish basalt types as similar as Ibitira and basaltic eucrites from vestan orbit.

CONCLUSIONS

The mean Fe/Mn ratio of low-Ca pyroxene (<10 mole% wo) in Ibitira is 36.4 ± 0.4 (1σ standard error of the mean), and is well resolved from those of five basaltic eucrites studied for comparison: 31.2–32.2. The Fe/Mn ratios for the latter completely overlap. Ibitira pyroxenes also have lower Fe/Mg (1.42 ± 0.03) than those of the basaltic eucrites (1.57–1.73). Thus, the higher Fe/Mn ratio does not reflect a simple difference in oxidation state. Rather, a more magnesian source slightly depleted in Mn for Ibitira is more plausible. Ibitira also has an oxygen isotopic composition (Wiechert et al. 2004), alkali element contents (Stolper 1977) and a Ti/Hf ratio that distinguish it from basaltic eucrites. These differences support derivation from a distinct parent asteroid. Although clearly distinct, Ibitira is nonetheless very similar to basaltic eucrites and basaltic clasts in mesosiderites in chemical and isotopic composition. This suggests the parent asteroid for Ibitira was formed within the same limited region of the asteroid belt as those of the latter.

The world's meteorite collection contains recognized fragments of basaltic crusts from five differentiated parent asteroids: the HED, mesosiderite, angrite, NWA 011, and Ibitira parent bodies. This is fewer than the number of differentiated asteroids estimated from the iron meteorite population, suggesting that differentiated asteroids with basaltic crusts would have been relatively common in the early solar system. Only one, 4 Vesta, has survived relatively intact. Astronomical evidence also suggests that some vestoids may be fragments of a completely disrupted differentiated asteroid. The challenges for the Dawn mission will thus include identification of distinct basalt types on 4 Vesta and determining whether it is, in fact, the HED parent asteroid.

Acknowledgments–I thank T. J. McCoy of the National Museum of Natural History at the Smithsonian Institution for providing the thin section of Ibitira and M. M. Grady of the British Museum (Natural History) for providing the sample of Sioux County used in this work. I thank the National Science Foundation for funding the ANSMET collecting teams that brought back the Antarctic samples studied here and the Meteorite Working Group, NASA Johnson Space Center, and the National Museum of Natural History (Smithsonian Institution) for allocation of the samples. I thank K. Yanai, H. Kojima, and the National Institute of Polar Research for providing the thin sections of Yamato-793164. I thank T. Hiroi and RELAB for making the spectral data available. Some of the microprobe data on Stannern were collected by K. G. Gardner as part of a summer internship; I thank her for her work. Reviews by an anonymous reviewer, J. L. Berkley, and A. Ruzicka, as well as editorial handling and review by C. A. Goodrich led to considerable improvement in the manuscript. I thank them for their good work. This study was funded by the NASA Cosmochemistry Program.

Editorial Handling—Dr. Cyrena Goodrich

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APPENDIX

Table A1. Average Na, Ca, Ti, and Hf data and Na/Ca and Ti/Hf ratios for the asteroidal basalts shown in Fig. 3.

Meteorite	Na mg/g	Ca mg/g	Ti mg/g	Hf µg/g	Na/Ca CI-normalized	Ti/Hf CI-normalized
Ibitira	1.47	77.6	5.02	1.16	0.0343	1.131
	Basaltic eucrites					
A-881388	3.26	75.5	2.50	1.06	0.0782	0.616
ALHA81001	2.62	70.4	5.28	2.16	0.0674	0.639
Béréba	3.30	76.0	4.66	1.25	0.0786	0.974
Bouvante	3.56	74.2	6.13	2.72	0.0869	0.589
Cachari	3.84	75.2	3.83	1.11	0.0924	0.902
Caldera	3.49	71.4	3.54	0.92	0.0885	1.006

Table A1. *Continued.* Average Na, Ca, Ti, and Hf data and Na/Ca and Ti/Hf ratios for the asteroidal basalts shown in Fig.

Meteorite	Na mg/g	Ca mg/g	Ti mg/g	Hf µg/g	Na/Ca CI-normalized	Ti/Hf CI-normalized
Camel Donga	3.84	72.4	4.66	1.43	0.0960	0.852
Chervony Kut	3.32	75.6	4.23	1.49	0.0795	0.742
Haraiya	3.15	71.5	3.28	1.02	0.0798	0.840
Jonzac	3.52	73.4	4.95	1.37	0.0868	0.944
Juvinas	3.17	76.2	3.75	1.20	0.0753	0.817
Lakangaon	3.85	74.1	5.38	1.60	0.0941	0.879
Millbillillie	3.38	73.5	4.15	1.14	0.0833	0.951
Nuevo Laredo	3.89	73.9	5.31	1.73	0.0953	0.802
Padvarninkai	3.18	74.0	3.68	1.34	0.0778	0.718
Palo Blanco Creek	3.15	75.4	4.13	1.15	0.0756	0.939
Pasamonte	3.84	74.9	4.13	1.45	0.0928	0.744
PCA 91007	3.52	72.8	4.40	1.49	0.0875	0.772
Piplia Kalan	3.63	74.4	4.50	1.26	0.0883	0.933
Pomozdino	3.48	71.4	4.83	2.21	0.0882	0.571
RKPA80204	3.05	71.0	4.60	1.30	0.0778	0.925
Sioux County	2.89	73.2	3.68	1.18	0.0715	0.815
Stannern	4.18	74.6	6.17	2.25	0.1014	0.717
Vetluga	3.38	71.3	4.20	1.39	0.0858	0.790
Y-791186	3.64	69.0	5.35	2.04	0.0955	0.685
Y-792510	3.38	74.2	4.45	1.37	0.0825	0.849
Y-793164	4.12	75.2	5.63	1.89	0.0992	0.779
Y-82037	2.89	75.3	2.80	0.97	0.0695	0.754
Y-82066	3.31	74.6	3.45	0.89	0.0803	1.013
	Angrites					
A-881371	0.16	81.2	5.30	1.03	0.0036	1.345
Angra dos Reis	0.25	165.2	13.10	2.31	0.0027	1.482
D'Orbigny	0.13	106.5	4.95	1.44	0.0022	0.898
LEW 86010	0.19	129.8	7.69	2.04	0.0027	0.985
LEW 87051	0.20	82.6	4.37	1.26	0.0044	0.906
Sahara 99555	0.12	108.0	5.50	1.80	0.0020	0.799
	Unique basaltic achondrite					
NWA 011	3.86	76.7	5.07	1.33	0.0911	0.996
	Mesosiderite primary basalt clasts					
Mount Padbury clast RV-05	3.27	68.1	4.30	0.88	0.0869	1.277
Vaca Muerta pebble 16	2.89	82.2	4.10	1.00	0.0636	1.072
Vaca Muerta clast 4677	2.30	64.3	4.40	0.79	0.0647	1.456
Vaca Muerta clast 4679	3.30	73.6	4.00	1.30	0.0812	0.804
Vaca Muerta clast 4695	3.20	71.3	3.10	1.19	0.0812	0.681

Table A2. Listing of data sources used to calculate meteorite averages.

Authors	Year	Journal	Notes
Allen and Mason	1973	GCA 37:1435	GCA = *Geochimica et Cosmochimica Acta*
Barrat et al.	2000	MAPS 35:1087	MAPS = *Meteoritics & Planetary Science*
Binns	1977	unpublished	
Blanchard	1981	BVSP A-11:70	BVSP = *Basaltic volcanism study project* (book)
Boctor et al.	1994	M 29:445	M = *Meteoritics*
Bogard and Garrison	1995	GCA 59:4317	
Bogard and Garrison	2003	MAPS 38:669	
Bogard et al.	1985	GCA 49:941	
Buchanan	–	unpublished	
Buchanan et al.	2000	MAPS 35:609	

Table A2. *Continued.* Listing of data sources used to calculate meteorite averages.

Authors	Year	Journal	Notes
Christophe Michel-Levy et al.	1987	BM 110:449	BM = *Bulletin of Mineralogy*
Cleverly et al.	1986	M 21:263	
Delaney et al.	1984	LPS 15:212	LPS = Lunar and Planetary Science Conference
Dickenson et al.	1985	CE 44:245	CE = *Chemie der Erde*
Duke and Silver	1967	GCA 31:1637	
Easton and Lovering	1964	ACA 30:543	ACA = *Analytica Chimica Acta*
Edwards	1955	GCA 8:285	
Edwards and Urey	1955	GCA 7:154	
Ehmann et al.	1979	ODE 2:247	ODE = *Origin and distribution of the elements* (book)
Fredriksson and Kraut	1967	GCA 31:1701	
Fukuoka	1990	ASAM 15:155	ASAM = Abstract, Symposium on Antarctic Meteorites
Gast	1962	GCA 26:927	
Gast et al.	1970	PLSC 1:1143	PLSC = Proceedings, Lunar and Planetary Science Conference
Higuchi and Morgan	1975	PLSC 6:1625	
Jarosewich	1990	M 25:323	
Jerome	1970	Ph.D., University of Oregon	
Jochum et al.	1980	M 15:31	
Jochum et al.	2000	MAPS 35:229	
Kharitonova and Barsukova	1982	RM 40:41	
Kiesl et al.	1967	MFC 98:972	MFC = *Monatshefte für Chemie*
Kimura et al.	1991	PNSAM 4:263	PNSAM = Proceedings, NIPR Symposium on Antarctic Meteorites
Kolesov and Hernandez	1984	RM 43:106	
Korotchantseva et al.	2003	LPS 34:1575	
Kurat et al.	2004	GCA 68:1901	
Kvasha and Dyakonova	1972	RM 31:109	RM = *Meteoritika* (in Russian)
Lee and Halliday	1997	N 388:854	N = *Nature*
Lodders	2003	AJ 591:1220	AJ = *Astrophysical Journal*
Ma et al.	1977	EPSL 35:331	
Mason	1983	AMNL 6,1:1	AMNL = *Antarctic Meteorite Newsletter*
Mason et al.	1979	SCES 22:45 p.	SCES = *Smithsonian Contributions to Earth Sciences*
McCarthy et al.	1973	EPSL 18:433	EPSL = *Earth and Planetary Science Letters*
McCarthy et al.	1974	M 9:215	
McKay et al.	1988	LPS 39:762	
Metzler et al.	1995	PSS 43:499	PSS = *Planetary and Space Science*
Mittlefehldt	1979	GCA 43:1917	
Mittlefehldt	–	unpublished	
Mittlefehldt and Lindstrom	1990	GCA 54:3209	
Mittlefehldt and Lindstrom	1993	PNSAM 6:268	
Mittlefehldt and Lindstrom	2003	GCA 67:1911	
Mittlefehldt et al.	2002	MAPS 37:345	
Miura et al.	1993	GCA 57:1857	
Morrison	1971	AAGC:51	AAGC = *Activation analysis in geochemistry and cosmochemistry* (book)
Palme and Rammensee	1981	PLPSC 12:949	
Palme et al.	1978	PLPSC 9:25	PLPSC = Proceedings, Lunar and Planetary Science Conference
Palme et al.	1988	M 23:49	
Patchett and Tatsumoto	1980	N 288:571	
Podosek and Huneke	1973	GCA 37:667	
Prinz et al.	1990	LPS 21:979	
Quitté et al.	2000	EPSL 184:83	
Rieder and Wänke	1969	MR:75	MR = *Meteorite research* (book)
Rubin and Mittlefehldt	1992	GCA 56:827	
Schaudy et al.	1967	CG 2:279	CG = *Chemical Geology*
Schmitt et al.	1972	M 7:131	
Shima	1979	GCA 43:353	
Shukla et al.	1997	MAPS 32:611	

Table A2. *Continued.* Listing of data sources used to calculate meteorite averages.

Authors	Year	Journal	Notes
Stolper	1977	GCA 41:587	
Tatsumoto et al.	1981	PSAM 6:237	PSAM = Proceedings, Symposium on Antarctic Meteorites
Tera et al.	1970	PLSC 1:1637	
Urey and Craig	1953	GCA 4:36	
Von Michaelis et al.	1969	EPSL 5:387	
Wänke and Konig	1959	ZN 14a:860	ZN = *Zeitschrift für Naturwissenshaften*
Wänke et al.	1972	PLSC 3:1251	
Wänke et al.	1974	PLSC 5:1307	
Wänke et al.	1977	PLSC 8:2191	
Warren and Jerde	1987	GCA 51:713	
Warren et al.	1990	PLPSC 20:281	
Warren et al.	1995	ASAM 20:261	
Warren et al.	1996	ASAM 21:195	
Weyer et al.	2002	CG 187:295	
Yamaguchi et al.	2002	S 296:334	S = *Science*
Yanai and Kojima	1995	CAM	CAM = *Catalog of the Antarctic meteorites* (book)
Yin et al.	2002	N 418:949	

Table A3. Listing of meteorites and data sources used in construction of Figs. 5 and 6. All spectra were acquired by T. Hiroi on samples ground to <25 μm using a bidirectional visible-near infrared spectrometer for the wavelength range 300–2600 nm, interval 5 nm, source angle 30° and detection angle 0°. The data are publicly available from the RELAB website (http://www.planetary.brown.edu/relab). See the RELAB website for additional details.

Meteorite	Type	Sample ID	RELAB file	Measurement date
Ibitira	Basaltic achondrite	MP-TXH-054-A	CAMP54	14 May 1997
Béréba	Basaltic eucrite	MP-TXH-089-A	CAMP89	05 March 1998
Bouvante	Basaltic eucrite	MP-TXH-090-A	CAMP90	05 March 1998
Cachari	Basaltic eucrite	MP-TXH-084-A	CAMP84	04 March 1998
Jonzac	Basaltic eucrite	MP-TXH-091-A	CAMP91	05 March 1998
Juvinas	Basaltic eucrite	MB-TXH-070-A	CAMB70	27 April 1993
Millbillillie	Basaltic eucrite	MB-TXH-069-A	CAMB69	27 April 1993
Padvarninkai	Basaltic eucrite	MB-TXH-096-C	CCMB96	01 December 1993
Pasamonte	Basaltic eucrite	MP-TXH-087-A	CAMP87	04 March 1998
Stannern	Basaltic eucrite	MB-TXH-097-A	CAMB97	20 October 1993
Binda	Cumulate eucrite	MP-TXH-082-A	CAMP82	03 March 1998
Moore County	Cumulate eucrite	MP-TXH-086-A	CAMP86	04 March 1998
Serra de Magé	Cumulate eucrite	MP-TXH-092-A	CAMP92	06 March 1998
Aïoun el Atrouss	Diogenite	MP-TXH-081-A	CAMP81	03 March 1998
Johnstown	Diogenite	MB-TXH-095-A	CAMB95	20 October 1993
Tatahouine	Diogenite	MP-TXH-088-A	CAMP88	05 March 1998
Bununu	Howardite	MP-TXH-083-A	CAMP83	03 March 1998
Frankfort	Howardite	MP-TXH-085-A	CAMP85	04 March 1998
Kapoeta	Howardite	MP-TXH-053-A	CAMP53	14 May 1997
Le Teilleul	Howardite	MP-TXH-093-A	CAMP93	06 March 1998
Petersburg	Polymict eucrite	MP-TXH-070-A	CAMP70	26 February1998