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Trace element constraints on the origins of highly metamorphosed Antarctic eucrites

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Abstract: We have compared the trace element distributions of four highly metamorphosed Antarctic eucrites with those of previously studied non-cumulate eucrites. All eucrites studied here exhibit some evidence for re-equilibration of the REE and/or other trace elements. LREE-enrichments are observed in the silicate phases, and are attributed to remobilization of the REE from Ca-phosphates. Similarly, elevated Zr and Ti abundances in some pigeonites may be the result of redistribution from oxide phases such as ilmenite. Thus, trace element distributions cannot provide petrogenetic information about the origin of these eucrites. However, combined with petrographic information, the data do provide information about the nature and degree of heating and metamorphism experienced by these rocks. For example, Y-86763 appears to have experienced a rapid secondary reheating, in addition to an extended period of thermal metamorphism.

Two granulitic eucrites appear to have been less extensively affected by metamorphism, despite the fact that they are strongly recrystallized. Although plagioclase REE compositions are LREE-enriched compared to those of non-cumulate eucrites, pigeonites have LREE/HREE ratios that fall close to the non-cumulate line. Furthermore, they seem to have retained their original Ti, Zr and Y abundances.

Finally, some trace elements, such as Na, K, Sr and Ba in plagioclase, do not appear to have been redistributed between mineral phases in these eucrites, and provide links to less equilibrated non-cumulate eucrites.

1. Introduction

The eucrites are part of the large group of achondrites known as HED (howardite-eucrite-diogenite) meteorites. Their oxygen isotopic compositions (Clayton *et al.*, 1976) suggest that they formed on a common parent body, often associated with the asteroid 4 Vesta (McCord *et al.*, 1970; Consolmagno and Drake, 1977; Binzel and Xu, 1993). Composed primarily of plagioclase and pigeonite, most non-cumulate eucrites probably formed as crustal rocks through the eruption of

basaltic lavas on (or intruded near) the surface of their parent body. Nevertheless, many of them have undergone post-crystallization processes such as brecciation, impact melting and, particularly, recrystallization as a result of thermal metamorphism (Takeda and Graham, 1991; Yamaguchi *et al.*, 1996a). The degree of metamorphism experienced by eucrites is variable and they have been classified as either equilibrated or unequilibrated (Reid and Barnard, 1979), based on the mineralogy of their pyroxenes. More recently, Takeda and Graham (1991) have suggested that the eucrites form a metamorphic sequence from type 1 to type 6. In this scheme, types 1–3 are comparable to the unequilibrated eucrites of Reid and Barnard (1979) and types 4–6 are comparable to the equilibrated eucrites. Type 7 eucrites have also been observed (Yamaguchi *et al.*, 1996a). These authors have, furthermore, suggested that thermal metamorphism of the eucrites took place during and after crust formation, through eruption, burial and reheating of lava flows. As the crust grew thicker, burial depth and temperatures increased, leading to widespread metamorphism of the eucrites. Only the last few percent of eucrites erupted (the unequilibrated eucrites) would have escaped significant metamorphism (Yamaguchi *et al.*, 1996a).

Despite the fact that many eucrites have undergone thermal metamorphism, ion microprobe studies of both non-cumulate and cumulate eucrites (Hsu and Crozaz, 1996, 1997a, b) have shown that many of them do, in fact, exhibit systematic trace element variations in pyroxene and plagioclase, which provide information about their petrogenetic histories and relationships to one another. For example, most non-cumulate eucrites have similar ratios of light rare earth elements (LREE) to heavy rare earth elements (HREE) in plagioclase and pyroxene, respectively (Hsu and Crozaz, 1996). Distributions of other trace elements (*e.g.*, Ti and Zr in pyroxene) also exhibit systematic variations that are generally consistent with the formation of Stannern and main group eucrites by different degrees of partial melting and of the Nuevo Laredo trend by fractional crystallization, as originally suggested by Stolper (1977). Furthermore, although highly metamorphosed eucrites, such as Ibitira (Hsu and Crozaz, 1996, 1997a) and EET90020 (Floss and Crozaz, 1997, 1998; Yamaguchi *et al.*, in preparation), have experienced redistribution of the rare earth elements (REE) from Ca-phosphates to plagioclase and pigeonite, in at least some instances other trace elements do not appear to have been affected by inter-mineral redistribution (*e.g.*, Floss and Crozaz, 1998).

In this work, we have examined the distributions of the REE and selected other trace elements in individual minerals from four highly equilibrated eucrites from Antarctica: Y-86763, A-87272, A-881388 and A-881467. Our goals were twofold: first we wanted to investigate in detail the effects of metamorphism on the distributions of trace elements in eucritic minerals; second we hoped that these data would provide, despite the effects of metamorphism, insights into the relationship of highly equilibrated eucrites to previously investigated non-cumulate eucrites (*i.e.*, Hsu and Crozaz, 1996, 1997a).

2. Experimental and sample descriptions

All samples studied were polished thin sections provided by the National Institute of Polar Research. Samples were documented and characterized using a Zeiss DSM 962 scanning electron microscope (SEM) and a Cameca Camebax electron microprobe. Additional documentation, prior to ion microprobe analyses, was carried out on JEOL 840A SEM.

Abundances of the REE and selected other trace elements were determined using the Washington University modified Cameca IMS-3f ion microprobe, according to techniques described by Zinner and Crozaz (1986a). All measurements were made using an O^- primary beam and energy filtering at low mass resolution to remove complex molecular interferences. The resulting mass spectrum was deconvolved to remove simple molecular interferences that are not eliminated with energy filtering, in order to obtain concentrations of the elements K-Ca-Sc-Ti, Rb-Sr-Y-Zr, and Ba-REE. Details of the analysis program are provided by Alexander (1994) and Hsu (1995). Sensitivity factors for the REE in pyroxene and Ca-phosphates are from Zinner and Crozaz (1986b) and those for plagioclase are from Floss and Jolliff (1998). Sensitivity factors for other elements in plagioclase and pyroxene are from Hsu (1995) and are listed in Table 1 of Floss *et al.* (1998). Silicate measurements were normalized using Si as a reference element; SiO_2 concentrations for plagioclase and pyroxene are from Yamaguchi *et al.* (1997a). Ca-phosphate measurements were normalized using Ca as a reference element and CaO concentrations obtained from quantitative EDS analyses. Analysis spots were carefully chosen prior to measurements in order to avoid cracks and inclusions commonly observed in eucritic minerals, and were examined afterwards to check for contamination in the third dimension. In addition, masses diagnostic of potential contaminating phases (*e.g.*, mass 31 for P) were continuously monitored during all analyses.

Petrologic observations of these meteorites have been reported by Yamaguchi *et al.* (1997a) and are summarized here, along with additional new observations.

Yamato 86763,51-2: this eucrite has a subophitic texture resembling that of EET90020 (Yamaguchi *et al.*, 1996b, 1997b). It is a type 5 eucrite, with large pigeonite crystals containing closely spaced thin augite lamellae. Plagioclase grains have narrow compositional ranges and the laths are mostly clear, although some contain minor inclusions. Recrystallized mesostasis is present as finer-grained intergrowths of tridymite, pyroxene and plagioclase. As in Ibitira and EET90020 (Yamaguchi *et al.*, 1997b; in preparation), we have found unusual textures related to oxide assemblages. The assemblages are generally composed of Ti-rich spinel and ilmenite. However, some of the spinel compositions extend to that of Cr-ulvöspinel ($Usp_{44.2}Chm_{44.1}$). The oxides in most cases are surrounded by thin rims (less than 15 μm thick) of pyroxene and Fe-rich olivine (Fa77.5–79.6) or both (Fig. 1). The rim pyroxenes have variable chemical compositions (Fig. 2) despite the fact that some of them are in contact with well-homogenized type 5 pyroxenes.

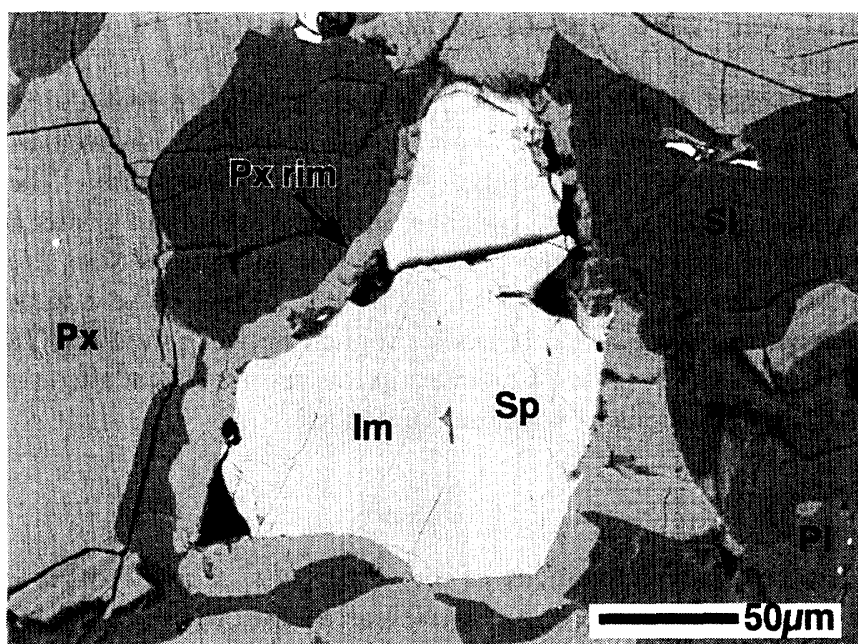


Fig. 1. Back-scattered electron image of oxides in Y-86763. The oxide assemblage, composed of Ti-spinel (Sp) and ilmenite (Im), is rimmed by pyroxene (Px rim). Px: pyroxene; Si: silica mineral; Pl: plagioclase.

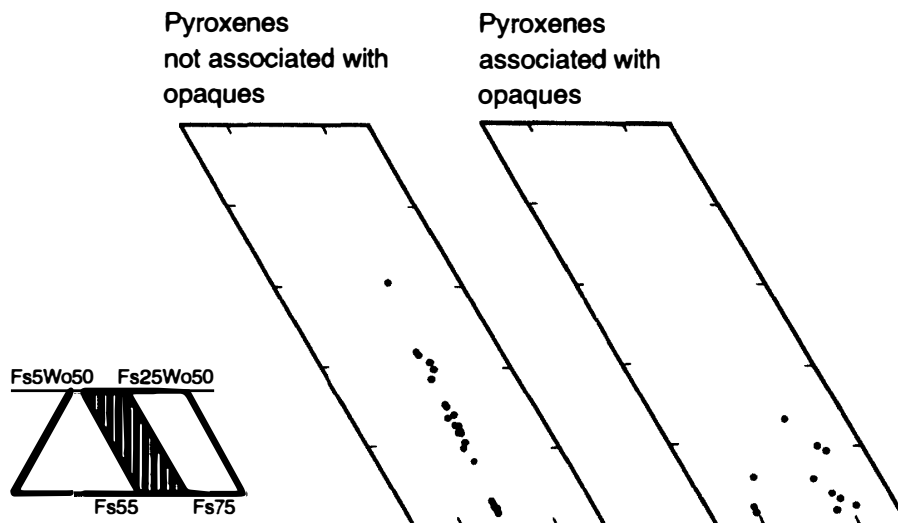


Fig. 2. Pyroxene compositions of Y-86763. The pyroxenes associated with oxide assemblages (see Fig. 1) show variable chemical compositions.

Asuka 87272,71-2: this is a monomict eucrite, which contains both coarse-grained regions with relict subophitic texture and fine-grained recrystallized granulitic areas. Pigeonites are partly inverted into orthopyroxene but have retained some remnant Ca-zoning and contain heterogeneously spaced augite lamellae (e.g., type 7 eucrite; Yamaguchi *et al.*, 1996a). Plagioclase grains have uniform compositions and are largely free of inclusions. This meteorite is highly shocked. The pyroxenes are extensively fractured and mosaicized; although plagioclase grains are

less fractured and have smooth surfaces, almost all of them have been maskelynitized.

Asuka 881388,54-2 and 881467,54-2: these eucrites are granulitic with highly recrystallized textures. Both pigeonite and augite are present, as well as plagioclase and minor amounts of silica minerals, oxides and Ca-phosphate. The pigeonites contain thin, closely spaced augite lamellae, but separate augite grains generally do not contain inclusions or exsolved phases. Pyroxene compositions are somewhat more magnesian in A-881388 than in A-881467. Plagioclase compositions are homogeneous within each eucrite, but differ slightly between the two (Yamaguchi *et al.*, 1997a). In A-881388 most plagioclase grains are clear, but those in A-881467 contain abundant inclusions of pyroxene and silica.

3. Results

We measured the abundances of the REE and selected other elements in plagioclase and pyroxene (pigeonite, as well as augite, where present) in the four eucrites described above. In addition, a Ca-phosphate grain large enough to analyze was found in one of the eucrites. Average concentrations are listed in Table 1, and representative REE patterns are shown in Fig. 3.

Plagioclase: REE patterns for plagioclase are LREE-enriched with large positive Eu anomalies. REE abundances are uniform within a given eucrite, but average abundances between the different meteorites vary by almost a factor of three (Fig. 3a). The REE are most enriched in Y-86763, with concentrations similar to those observed in some parts of EET90020 (Floss and Crozaz, 1997, 1998; Yamaguchi *et al.*, in preparation).

Pyroxene: pigeonite was analyzed in each eucrite. The REE patterns are HREE-enriched with pronounced negative Eu anomalies. Augite is present as discrete grains in the two granulitic eucrites, A-881388 and A-881467. The REE patterns of augites are also HREE-enriched, but have higher concentrations, shallower slopes, and smaller Eu anomalies than the patterns of pigeonites (Fig. 3b). The granulitic eucrites appear to be very similar: both pigeonite and augite from each eucrite have almost identical REE abundances. As also noted for plagioclase, REE concentrations in pigeonite from Y-86763 are higher than those of other eucrites.

In general, REE concentrations in the pyroxenes are uniform within a given meteorite. However, the pyroxenes analyzed in A-87272 exhibit variable REE abundances (Fig. 3c) that correlate with Ca concentrations. The range of compositions observed is listed in Table 1. As noted above, A-87272 contains both thin and thick augite lamellae, that are heterogeneously spaced within their host pigeonites. The variable REE abundances observed in the pyroxene analyses reported here reflect heterogeneous sampling of these lamellae during our measurements. Furthermore, all pyroxene REE patterns from this eucrite exhibit positive Ce anomalies whose magnitudes (expressed as Ce/Ce^* where Ce^* is the interpolated value between CI-normalized La and Pr abundances) range from 2.5 to 8.2. These

Table 1. Average major, minor and trace element concentrations in eucritic minerals*.

	A-881388, 54-2			A-881467, 54-2		
	plagioclase (3)	pigeonite (4)	augite (3)	plagioclase (4)	pigeonite (4)	augite (3)
Na	7553 ± 947	99 ± 15	681 ± 13	8141 ± 598	134 ± 34	883 ± 153
Mg	101 ± 5	8.1 %	6.9 %	99 ± 9	7.5 %	6.5 %
K	506 ± 68	19 ± 9	50 ± 26	572 ± 41	29 ± 7	97 ± 45
Ca	11.3 %	1.5 %	11.2 %	11.1 %	1.5 %	10.9 %
Sc	3.4 ± 0.2	34 ± 1	97 ± 1	3.2 ± 0.4	37 ± 7	95 ± 1
Ti	29 ± 1	1154 ± 42	2812 ± 40	34 ± 6	1062 ± 141	2705 ± 379
Fe	1256 ± 27	24.1 %	14.9 %	1440 ± 299	25.1 %	18.7 %
Sr	102 ± 3	0.15 ± 0.03	3.93 ± 0.26	111 ± 2	0.28 ± 0.07	4.47 ± 0.60
Y	0.36 ± 0.01	8.4 ± 0.2	32 ± 1	0.41 ± 0.08	9.7 ± 1.9	34 ± 2
Zr	0.038 ± 0.017	2.33 ± 0.25	40 ± 2	0.049 ± 0.038	2.49 ± 0.70	41 ± 10
Ba	27 ± 2	0.089 ± 0.075	0.16 ± 0.14	31 ± 2	0.15 ± 0.06	0.50 ± 0.15
La	0.68 ± 0.01	0.014 ± 0.009	0.55 ± 0.01	0.81 ± 0.08	0.014 ± 0.003	0.56 ± 0.09
Ce	1.42 ± 0.12	0.069 ± 0.024	3.13 ± 0.18	1.56 ± 0.22	0.090 ± 0.017	3.00 ± 0.29
Pr	0.14 ± 0.01	0.019 ± 0.004	0.76 ± 0.07	0.15 ± 0.02	0.026 ± 0.002	0.74 ± 0.08
Nd	0.54 ± 0.01	0.17 ± 0.02	4.34 ± 0.22	0.64 ± 0.06	0.20 ± 0.03	4.53 ± 0.51
Sm	0.10 ± 0.03	0.13 ± 0.03	2.16 ± 0.09	0.13 ± 0.01	0.13 ± 0.04	2.18 ± 0.27
Eu	0.97 ± 0.09	b.d.	0.013 ± 0.011	1.13 ± 0.03	b.d.	0.045 ± 0.009
Gd	0.045 ± 0.015	0.26 ± 0.06	2.98 ± 0.38	0.098 ± 0.025	0.36 ± 0.07	2.75 ± 0.29
Tb	0.009 ± 0.001	0.087 ± 0.013	0.68 ± 0.03	0.022 ± 0.008	0.11 ± 0.02	0.57 ± 0.02
Dy	0.044 ± 0.007	0.86 ± 0.05	4.86 ± 0.42	0.063 ± 0.009	1.04 ± 0.21	4.89 ± 0.11
Ho	0.012 ± 0.007	0.23 ± 0.03	0.94 ± 0.10	0.022 ± 0.005	0.26 ± 0.05	0.91 ± 0.04
Er	0.030 ± 0.008	0.91 ± 0.04	2.94 ± 0.23	0.035 ± 0.016	1.10 ± 0.21	2.94 ± 0.62
Tm	0.002 ± 0.004	0.15 ± 0.01	0.37 ± 0.03	0.002 ± 0.004	0.17 ± 0.04	0.39 ± 0.03
Yb	0.028 ± 0.003	1.07 ± 0.10	2.43 ± 0.33	0.021 ± 0.021	1.44 ± 0.29	2.63 ± 0.34
Lu	b.d.	0.21 ± 0.03	0.39 ± 0.12	b.d.	0.27 ± 0.01	0.33 ± 0.01

	Y-86763, 51-2			A-87272, 71-2		
	plagioclase (8)	pigeonite (10)	merrillite (1)	plagioclase (8)	pyx low (1)	pyx high (1)
Na	7359 ± 452	183 ± 8		6406 ± 297	74 ± 1	587 ± 3
Mg	313 ± 103	7.8 %		34 ± 4	8.3 %	7.0 %
K	429 ± 35	18 ± 6		441 ± 76	38 ± 1	64 ± 1
Ca	11.7 %	2.9 %		11.5 %	1.3 %	11.5 %
Sc	3.5 ± 0.4	39 ± 2		3.2 ± 0.3	35 ± 1	90 ± 1
Ti	82 ± 3	2590 ± 61		27 ± 8	1339 ± 4	2260 ± 7
Fe	1997 ± 475	23.3 %		1037 ± 115	26.7 %	11.8 %
Sr	117 ± 2	0.57 ± 0.06		111 ± 3	1.09 ± 0.07	5.1 ± 0.3
Y	0.62 ± 0.03	16 ± 1		0.26 ± 0.05	7.75 ± 0.21	27 ± 1
Zr	0.16 ± 0.04	36 ± 2		0.063 ± 0.031	2.65 ± 0.12	25 ± 1
Ba	34 ± 1	0.044 ± 0.049		32 ± 9	0.32 ± 0.03	0.41 ± 0.05
La	1.72 ± 0.09	0.13 ± 0.02	2874 ± 31	0.72 ± 0.15	0.080 ± 0.010	0.56 ± 0.05
Ce	3.50 ± 0.11	0.76 ± 0.04	7601 ± 56	1.40 ± 0.29	1.10 ± 0.09	5.40 ± 0.28
Pr	0.42 ± 0.03	0.19 ± 0.03	1009 ± 18	0.15 ± 0.03	0.055 ± 0.006	0.49 ± 0.05
Nd	1.42 ± 0.04	1.28 ± 0.07	5059 ± 51	0.52 ± 0.10	0.36 ± 0.02	3.86 ± 0.18
Sm	0.25 ± 0.03	0.71 ± 0.05	1136 ± 35	0.075 ± 0.025	0.13 ± 0.02	1.74 ± 0.14
Eu	1.22 ± 0.08	0.010 ± 0.004	14 ± 2	1.16 ± 0.05	b.d.	0.036 ± 0.014
Gd	0.18 ± 0.03	1.19 ± 0.11	1085 ± 46	0.082 ± 0.022	0.39 ± 0.03	2.92 ± 0.22
Tb	0.025 ± 0.007	0.28 ± 0.03	166 ± 11	0.008 ± 0.004	0.099 ± 0.010	0.59 ± 0.07
Dy	0.12 ± 0.01	2.16 ± 0.12	948 ± 25	0.049 ± 0.008	0.98 ± 0.06	3.88 ± 0.20
Ho	0.031 ± 0.006	0.51 ± 0.03	175 ± 9	0.021 ± 0.006	0.24 ± 0.02	0.94 ± 0.08
Er	0.055 ± 0.013	1.69 ± 0.09	388 ± 16	0.035 ± 0.007	0.88 ± 0.06	3.05 ± 0.14
Tm	0.005 ± 0.006	0.26 ± 0.03	48 ± 5	0.007 ± 0.008	0.19 ± 0.02	0.37 ± 0.04
Yb	0.048 ± 0.014	1.78 ± 0.13	223 ± 19	0.030 ± 0.007	1.22 ± 0.11	2.81 ± 0.29
Lu	b.d.	0.32 ± 0.04	30 ± 6	b.d.	0.22 ± 0.03	0.47 ± 0.07

*concentrations are in ppm, except as otherwise noted; errors are 1 σ , from counting statistics, for individual measurements, or standard deviation of the mean; the number of analyses are given in parentheses; b.d.: below detection.

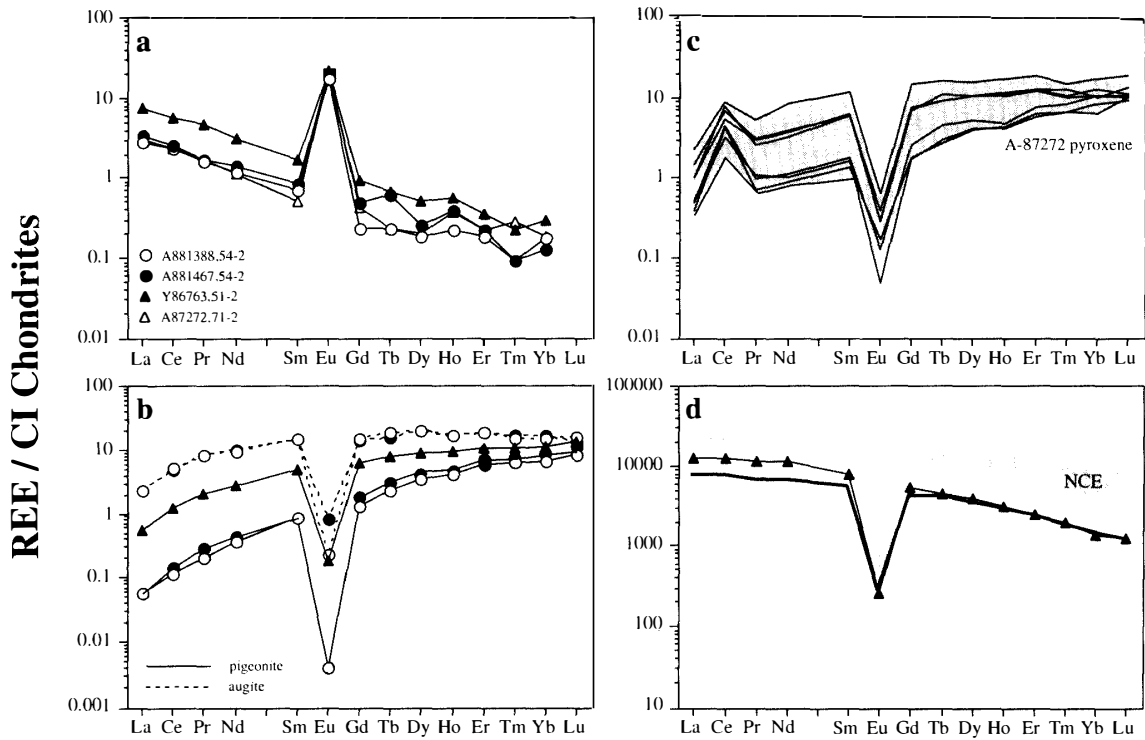


Fig. 3. CI chondrite-normalized REE patterns for (a) plagioclase; (b) pigeonite and augite; (c) pyroxene from A-87272; and (d) Ca-phosphate from Y-86763. All REE patterns show average abundances, except for (c) which shows the range of compositions observed. The shaded region in (d) shows the range of REE abundances observed in merrillite from non-cumulate eucrites (NCE) and the solid line shows REE abundances in Ibitira merrillite (data from Hsu and Crozaz, 1996). Symbols in (b) and (d) are the same as in (a).

anomalies may be attributed to redistribution of the REE during terrestrial weathering and are discussed in more detail below.

Phosphates: a single Ca-phosphate grain (a merrillite) large enough to analyze with the ion microprobe was found in Y-86763. It has a LREE-enriched pattern with a negative Eu anomaly (Fig. 3d); abundances are similar to those observed in Ibitira and are two to four times lower than those of merrillite in other non-cumulate eucrites (Hsu and Crozaz, 1996).

In addition to the REE, we measured other major, minor and trace element concentrations in plagioclase and pyroxene (Table 1). In Fig. 4 the abundances of Na, K, Sr and Ba in plagioclase from the four eucrites studied here are shown relative to the abundances of these elements in non-cumulate eucrites studied by Hsu and Crozaz (1996). All of these elements have narrow compositional ranges that fall within fields previously defined for non-cumulate eucrites (Fig. 4). Pyroxene compositions exhibit more complex variations (Fig. 5). Abundances of Ti, Zr and Y in pigeonite from Y-86763 exhibit enrichments similar to those previously observed for Ibitira (Hsu and Crozaz, 1996) and EET90020 (Floss and Crozaz, 1998; Yamaguchi *et al.*, in preparation), whereas the abundances of these elements in pigeonites from A-881388 and A-881467 fall within the non-cumulate fields.

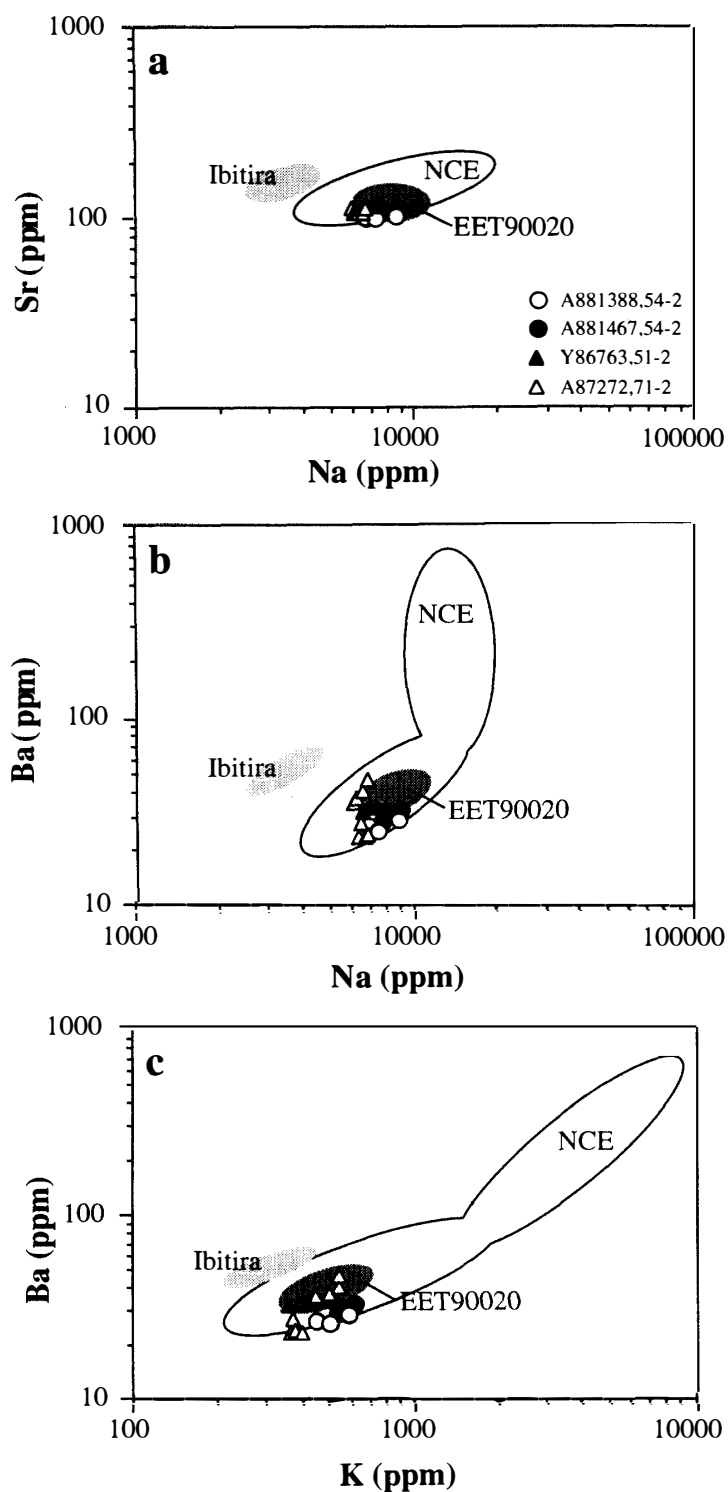


Fig. 4. Scatter plots of (a) Na vs. Sr, (b) Na vs. Ba, and (c) K vs. Ba in eucritic plagioclase. Outlined areas show fields for non-cumulate eucrites (NCE) and light and dark shaded areas show fields for Ibitira (data from Hsu and Crozaz, 1996) and EET90020 (data from Yamaguchi et al., in preparation), respectively.

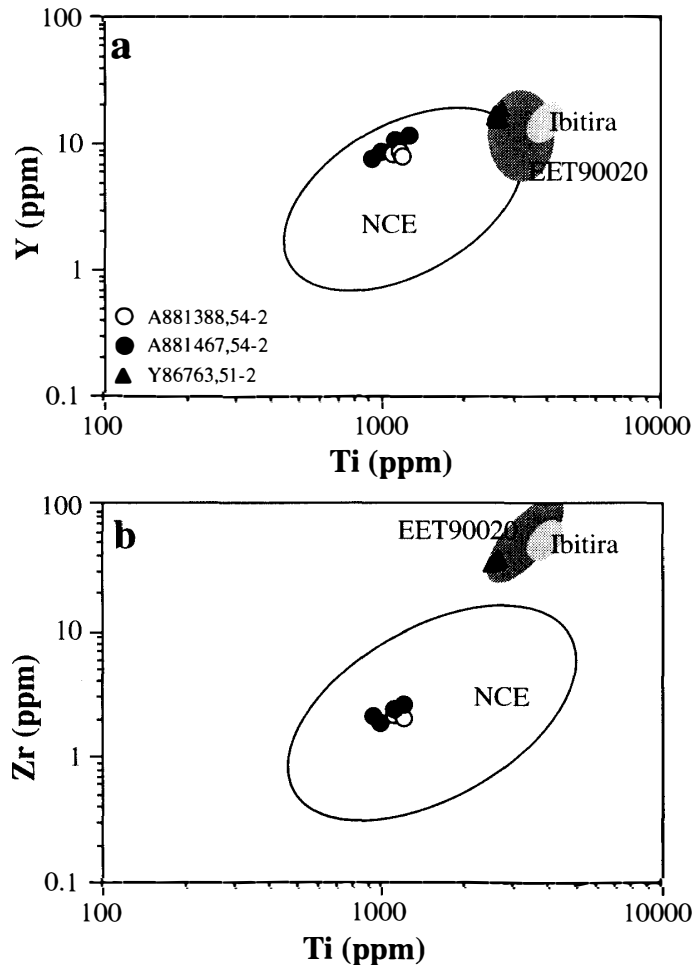


Fig. 5. Scatter plots of Ti vs. (a) Y and (b) Zr in eucritic pigeonite. Outlined areas show fields for non-cumulate eucrites (NCE) and light and dark shaded areas show fields for Ibitira (data from Hsu and Crozaz, 1996) and EET90020 (data from Yamaguchi *et al.*, in preparation), respectively.

Elemental abundances in pyroxene from A-87272 may have been affected by terrestrial weathering and redistribution (see below), and are not shown in Fig. 5.

4. Discussion

4.1. Ce anomalies in A-87272

Ce anomalies have been observed in numerous Antarctic meteorites (Lundberg *et al.*, 1990; Floss and Crozaz, 1991; Harvey *et al.*, 1993; Wadhwa *et al.*, 1994; Hsu and Crozaz, 1996). In the eucrites, they are found in both plagioclase and pyroxene and have been attributed to remobilization of the REE through terrestrial weathering of phosphates (Mittlefehldt and Lindstrom, 1991). During this process Ce^{3+} is oxidized to the more insoluble Ce^{4+} , leading to the preferential retention of this element over the trivalent REE. Ce anomalies are most pervasive in the presence of networks of shock-induced fractures and microcracks along which the REE may be mobilized (Floss and Crozaz, 1991; Hsu and Crozaz, 1996). The extensive

fracturing of pyroxene in A-87272 most likely accounts for the presence of Ce anomalies in this phase. Because redistribution of the REE in pyroxene may be accompanied by alteration-induced variations of other elements, data for A-87272 pyroxene cannot be used to interpret the origin of this meteorite. Plagioclase (maskelynite), on the other hand, is much less fractured and does not exhibit Ce anomalies in this eucrite; its minor and trace element compositions appear to have been unaffected by terrestrial weathering.

4.2. LREE-enrichments in equilibrated eucrites

Figure 6 shows the abundances of La vs. Y in plagioclase and of Yb vs. Sm in pigeonite from the eucrites; these elements illustrate the relationships between the LREE and HREE in these minerals. Hsu and Crozaz (1996) noted that most non-cumulate eucrites fall along a single correlation line, which for plagioclase also

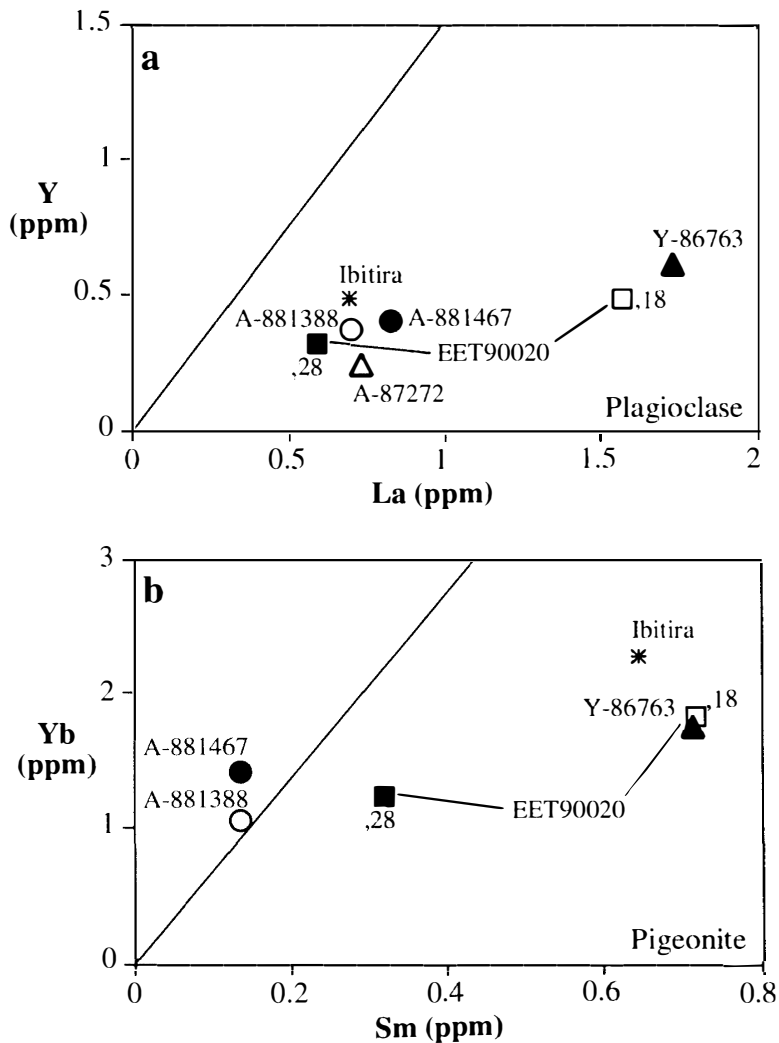


Fig. 6. Plots of (a) La vs. Y in plagioclase and (b) Sm vs. Yb in pigeonite. The solid lines represent correlations of these elements observed in non-cumulate eucrites. Data for non-cumulate eucrites and Ibitira from Hsu and Crozaz (1996); data for EET90020 from Yamaguchi et al. (in preparation).

represents the abundances expected for crystallization from melts with chondritic proportions of the REE. However, they also found that in the highly metamorphosed eucrite Ibitira, both plagioclase and pigeonite REE compositions are LREE-enriched and fall to the right of these lines. Furthermore, Floss and Crozaz (1997, 1998) examined the trace element distributions of another highly metamorphosed eucrite, EET90020, and found evidence for a heterogeneous distribution of the REE. Both plagioclase and pigeonite exhibit greater degrees of LREE-enrichment in a portion of the eucrite which, texturally, appears to have undergone more extensive heating (Yamaguchi *et al.*, in preparation).

The eucrites studied here generally also have LREE-enriched mineral compositions compared to most non-cumulate eucrites studied by Hsu and Crozaz (1996). For plagioclase, most of the eucrites fall close to Ibitira (Fig. 6a). However, Y-86763 exhibits much larger degrees (by about a factor of 3) of LREE-enrichment, similar to those observed in section ,18 of EET90020. The REE composition of pigeonite from Y-86763 is similar to that of Ibitira, as well as EET90020,18, and exhibits a higher degree of enrichment than that from EET90020,28 (Fig. 6b). However, pigeonites from the two granulitic eucrites, A-881388 and A-881467, fall close to the non-cumulate eucrite trend.

Hsu and Crozaz (1996, 1997a) suggested that the LREE-enrichments observed in plagioclase and pigeonite from Ibitira were the result of extensive re-equilibration of the REE between Ca-phosphates and the silicate minerals. Specifically, they noted that REE concentrations in Ibitira merrillite are significantly lower than those in merrillite from other non-cumulate eucrites (see Fig. 3d), and suggested that partial melting of the mesostasis, which contains the phosphates, and interaction of this melt with plagioclase and pigeonite produced the LREE-enriched signature (Hsu and Crozaz, 1997a). Merrillite would ultimately crystallize from the partial melt with lower REE concentrations. Floss and Crozaz (1997, 1998) concluded that redistribution of the REE from phosphates to silicates could account for the LREE-enrichments noted in EET90020 as well. REE concentrations in merrillite from Y-86763 are also lower than those in non-cumulate eucrites (Fig. 3d) studied by Hsu and Crozaz (1996). Although no Ca-phosphates large enough to analyze with the ion microprobe were found in the other eucrites studied here, it is likely that a mechanism similar to that postulated for Ibitira and EET90020 is responsible for the LREE-enrichments observed in all of these eucrites.

Yamaguchi *et al.* (1996b) also invoked partial melting of mesostasis in very highly metamorphosed eucrites, such as Ibitira and EET90020. Tridymite crystals, generally thought to form during metamorphism of eucrites, are so large in Ibitira and EET90020, that solid state processes are probably too slow to account for their formation. These authors suggested that partial melting of low temperature assemblages, implying peak metamorphic temperatures close to or exceeding the melting temperatures of eucrites ($\sim 1060^{\circ}\text{C}$), could account for the large crystal sizes. Tridymite is present as relatively large ($\leq 300\ \mu\text{m}$) blebs and grains in all eucrites investigated here, indicative of the high degrees of metamorphism the meteorites have experienced, although no grains are as large as those found in Ibitira

and EET90020. Furthermore, the chemical compositions of spinels in the eucrites studied here (see Yamaguchi *et al.*, 1997a) are similar to those observed in annealing experiments carried out on eucrites by Arai *et al.* (1998). These experiments were performed at near solidus temperatures (1050°C), implying that these eucrites experienced high temperature annealing, consistent with the peak metamorphic temperatures estimated from pyroxene chemistry (Yamaguchi *et al.*, 1997a).

4.3. *Secondary reheating and heterogeneous redistribution of the REE*

In addition to extensive thermal metamorphism, Yamaguchi *et al.* (1997b; in preparation) have suggested that Ibitira and EET90020 experienced an episode of rapid reheating and cooling, possibly as the result of a large impact event. The basis for this suggestion comes from the presence of compositionally variable phases co-existing with well-equilibrated host material in these meteorites; opaque minerals (Ti-rich spinel and ilmenite of metamorphic origin) are surrounded by thin rims of compositionally variable pigeonite and Fe-rich olivine in contact with equilibrated type 5 pyroxenes. These phases may have formed by rapid crystallization of partial melts or reaction with surrounding minerals. REE element data for EET90020 are consistent with this suggestion and, furthermore, provide evidence for variable degrees of reheating and REE redistribution within a single meteorite (Floss and Crozaz, 1998; Yamaguchi *et al.*, in preparation). Both plagioclase and pigeonite in EET90020,18 have higher REE abundances and larger LREE enrichments (Fig. 6) than their counterparts in EET90020,28, suggesting that this portion (*i.e.*, section ,18) of EET90020 experienced greater degrees of heating than other parts of the meteorite. Textural evidence also indicates more extensive heating, to the point of partial melting, in EET90020,18 (Floss and Crozaz, 1998; Yamaguchi *et al.*, in preparation).

Both the REE data and mineralogical observations suggest that Y-86763 may have experienced a thermal history similar to that discussed above for Ibitira and EET90020. The mineralogy and texture of Y-86763 are very similar to those of EET90020 and this eucrite contains compositionally variable rims on oxide grains like those observed in Ibitira and EET90020 (Figs. 1, 2; see also Section 2). Furthermore, the LREE-enrichments in both plagioclase and pigeonite are similar to those seen in EET90020,18 (Fig. 6).

4.4. *LREE/HREE ratios in pigeonite from granulitic eucrites*

As noted above, LREE/HREE ratios in pigeonite from the two granulitic eucrites, A-881388 and A-881467, are similar to those observed in non-cumulate eucrites, although plagioclase compositions show LREE-enrichments similar to those of Ibitira (Fig. 6). There are two possible explanations for this discrepancy. One possibility is that pyroxene may be less affected by redistribution of the REE than plagioclase. Although this appears counterintuitive given the fact that pigeonite, with its lower LREE concentrations and more rapid REE diffusion rates, should exhibit the effects of REE re-equilibration with Ca-phosphates more readily than plagioclase, it is nevertheless consistent with trace element data that will be

discussed below. An alternative explanation is suggested by the fact that, in addition to pigeonite, these granulitic eucrites contain augite thought to have formed during thermal metamorphism (Yamaguchi *et al.*, 1997a). The LREE may have been preferentially incorporated into augite relative to pigeonite during recrystallization and subsolidus growth, leaving pigeonite REE compositions essentially unchanged. A similar process has been suggested for augite derived from the inversion of primary pigeonite in lunar highlands rocks (James *et al.*, 1998). Additional data from two pyroxene eucrites will be required to fully resolve which of these two explanations accounts for the LREE/HREE ratios in the pigeonites. In either case, however, the ratios appear to reflect those of the original pyroxene to crystallize in these eucrites.

4.5. *Distributions of other trace elements in plagioclase and pigeonite*

Although REE distributions in plagioclase and pigeonite from these eucrites do not offer clues to their petrogenetic origins, the distributions of several other trace elements appear to provide links to the non-cumulate eucrites. Figure 4 shows the abundances of Na, K, Sr and Ba in plagioclase from the four eucrites studied here, relative to the compositional ranges observed for these elements in non-cumulate eucrites, Ibitira (Hsu and Crozaz, 1996) and EET90020 (Yamaguchi *et al.*, in preparation). As noted earlier, these elements have narrow ranges that fall within the fields defined for non-cumulate eucrites, suggesting that although homogenization may have occurred within plagioclase, abundances of these elements have not been affected by inter-mineral redistribution.

Distributions of other trace elements in pigeonite from the eucrites studied here are more complex than those in plagioclase (Fig. 5). Although abundances of Ti, Zr and Y in the pigeonite from the two granulitic eucrites, A-881388 and A-881467, fall within the fields previously defined for non-cumulate eucrites (Hsu and Crozaz, 1996), the abundances of these elements in Y-86763 are enriched relative to non-cumulate eucrite values, and are similar to those observed for Ibitira and EET 90020. Hsu and Crozaz (1996) suggested that diffusion of these elements from merrillite (Y) and oxide phases (Zr, Ti) could account for the elevated values seen in Ibitira; a similar redistribution probably accounts for the high values observed in Y-86763 and EET90020.

The fact that pigeonites from the granulitic eucrites seem to have retained their original Ti, Zr and Y abundances, whereas other eucrites did not, provides some indirect support for the suggestion, made above, that these pigeonites have not been affected by redistribution of the REE. This observation, however, is not easily understood in terms of the textural features of these eucrites. The relatively coarse-grained granulitic nature of both A-881388 and A-881467 suggests extensive annealing and recrystallization of what were originally probably brecciated basaltic eucrites (Yamaguchi *et al.*, 1997a). In contrast, Y-86763, as well as EET90020, have retained relict igneous textures, but have trace element signatures that imply greater degrees of elemental redistribution. A possible reconciliation of this discrepancy may be found by considering the suggestion of Yamaguchi *et al.*

(1997b) that eucrites such as EET90020 and Ibitira, as well as Y-86763, may have experienced a second, possibly impact-induced, reheating event following extensive thermal metamorphism. These eucrites all contain unequilibrated silicate rims around oxide grains, and show signs of extensive elemental redistribution (*e.g.*, Figs. 5, 6). The two granulitic eucrites, on the other hand, although they have recrystallized textures and exhibit some evidence of redistribution of the REE (*e.g.*, plagioclase LREE/HREE ratios; Fig. 6a), do not contain evidence for a second heating event. Thus, the higher degrees of elemental redistribution observed in Y-86763, EET90020 and Ibitira (*i.e.*, redistribution of Zr and Ti in pyroxene, more extensive REE redistribution) may result from rapid reheating of these meteorites, possibly through an impact event, in addition to the extensive subsolidus metamorphism experienced by all of the eucrites studied here.

5. Conclusions

The four highly metamorphosed eucrites we have studied all exhibit some evidence for redistribution of the REE and/or other trace elements in their silicate phases, relative to trace element relationships observed in previously studied non-cumulate eucrites. Thus, trace element distributions in highly metamorphosed eucrites cannot provide petrogenetic information about their origin. However, combined with petrographic information, the trace element data can provide information about the nature and degree of heating and metamorphism experienced by these rocks. For example, we noted that Y-86763, EET90020, and Ibitira probably experienced similar thermal histories that included an extended period of thermal metamorphism followed by a rapid reheating and cooling event.

Two granulitic eucrites appear to have been less extensively affected by metamorphism. Although plagioclase REE compositions are LREE-enriched compared to non-cumulate eucrites, pigeonites have LREE/HREE ratios that fall close to the non-cumulate line and, furthermore, seem to have retained their original Ti, Zr and Y abundances.

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