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Lithic components in the paired howardites EET 87503 and EET 87513: Characterization of the regolith of 4 Vesta

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Abstract: The matrix and twenty four clasts from the paired howardites EET 87503 and EET 87513 were studied by petrographic observation, instrumental neutron activation analysis (INAA), and electron microprobe analysis. Materials that presumably were affected by moderate to high degrees of shock include impact-melt breccias and eucritic clasts with blackened pyroxenes. Eucritic clasts were derived from cumulate eucrites, main-group eucrites, and evolved eucrites that are more Fe-rich than Nuevo Laredo, and include unequilibrated and equilibrated materials. Several of the diogenitic clasts are orthopyroxenite breccias that are much finer-grained than typical diogenites. Bulk compositions and mineral compositions of matrix and clasts indicate that EET 87513 can be modeled as a mixture, by weight, of 30% diogenite, 17% cumulate eucrite, 25% main-group eucrite, 25% Nuevo Laredo-trend eucrite, and 3% CM2 chondrite. The character of this mixture is probably related to the depth of excavation by impact processes on 4 Vesta and these meteorites may be appropriate as approximate analogues for portions of the surface regolith. The relatively large proportion of CM2 material in this mixture, compared with the relatively small number of carbonaceous chondrite clasts observed in thin sections, suggests that much of this CM2 material is present as sub-microscopic particles between individual mineral fragments and clasts.

key words: achondrite, howardite, regolith, lithic clasts, CM2

1. Introduction

The HED suite is composed of three types of meteorites: howardites, eucrites, and diogenites (see Mittlefehldt *et al.*, 1998 for a summary of HED petrology). Eucrites, which are mostly breccias, are basalts and gabbros predominantly composed of pyroxene and plagioclase. These volcanic/igneous rocks include cumulates formed by fractional crystallization of mafic magmas. Also included are trace element-rich primitive basalts (Stannern-trend eucrites) and a sequence of rocks ranging from trace element-poor primitive basalts to iron- and trace element-rich evolved basalts (main-group–Nuevo Laredo-trend eucrites). Diogenites, which are also mostly breccias, are magnesian orthopyroxenites with a fairly limited lithologic diversity. Howardites are polymict breccias composed of mixtures of mineral and lithic fragments derived from basalts, gabbros, and orthopyroxenites, *i.e.* materials identical to eucrites and diogenites. Together, the fragmental breccias of the HED suite of meteorites represent the regolith of a differentiated asteroid.

The howardites Elephant Moraine (EET) 87503 (1734.5 g) and EET 87513 (394.5 g) were collected on the Texas Bowl ice field in Antarctica. Hand specimen and thin section examination suggests that both meteorites are relatively unaltered (alteration classification A and A/B, respectively). Both meteorites are typical howardites with fragmental brecciated textures (Figs. 1a and 1b) and pyroxenes that range from magnesian orthopyroxenes, similar to those found in diogenites, to Fe-rich pyroxenes containing augite exsolution lamellae in a low Ca pyroxene host, similar to those found in the evolved eucrite Nuevo Laredo. Hence, these meteorites contain a wide variety of diogenitic and eucritic materials. Based on textural and bulk compositional similarities, Buchanan *et al.* (2000) concluded that these two meteorites are paired. Six other howardites are listed as paired with EET 87503 in the NASA-Johnson Space Center (JSC) curatorial database. However, these meteorites may represent separate falls (Buchanan *et al.*, 2000).

Hiroi *et al.* (1994) compared the reflectance spectra of the asteroid 4 Vesta with laboratory-acquired reflectance spectra of different grain size fractions ($<$25, 25–45, 45–75, and 75–125 μm) of six HED meteorites, including three eucrites (Millbillillie, Juvinas, and Y-74450), one howardite (EET 87503), and two diogenites (Y-74013 and Y-75032). Of these meteorites, the spectrum of the finest grain-size fraction of EET 87503 was most similar to that of the asteroid (Hiroi *et al.*, 1994). Reflectance spectra, in general, provide information averaged over relatively large areas (10s to 100s of km) about surface materials; in the case of 4 Vesta, the reflectance spectra are strongly influenced by the compositional range of pyroxenes (Binzel *et al.*, 1997; Gaffey, 1997; Burbine *et al.*, 2001). Hence, the howardites EET 87503 and EET 87513 may contain similar relative proportions of diogenitic and eucritic components as portions of the surface regolith of 4 Vesta (*e.g.,* Burbine *et al.*, 2001). However, it must be noted, based on detailed spectroscopy, that 4 Vesta shows lithologic diversity across its surface (Binzel *et al.*, 1997; Gaffey, 1997). Thus, no single meteorite can represent all regions of the asteroid's regolith. Nevertheless, the study of meteorites that approximate portions of the Vestan surface regolith can provide important clues for the crustal stratigraphy and differentiation history of the asteroid (*e.g.* Warren, 1985, 1997).

The compositions of matrix mineral fragments in howardites have previously been used to infer the types of source rocks contributing debris to these polymict breccias (*e.g.* Labotka and Papike, 1980; Fuhrman and Papike, 1981; Ikeda and Takeda, 1984; Reid *et al.*, 1990). However, compositions of individual pyroxene and feldspar fragments alone do not always allow definitive identification of the types of eucrites that contributed to these breccias. For example, the pyroxenes in the incompatible element-rich eucrite Stannern and those in the main-group eucrite Juvinas are only slightly different in Mg# ($=100\,\mathrm{Mg}/(\mathrm{Mg}+\mathrm{Fe})$, atomic proportions) (Basaltic Volcanism Study Project, 1981). Feldspars in Stannern are only slightly less anorthite-rich, on average, than feldspars in Nuevo Laredo (Basaltic Volcanism Study Project, 1981). There are also difficulties in attempting to use bulk compositions to estimate proportions of various petrologic/geochemical types of eucrites in howardites because the different eucrite types have only modest differences in composition (*e.g.,* Kitts and Lodders, 1998).

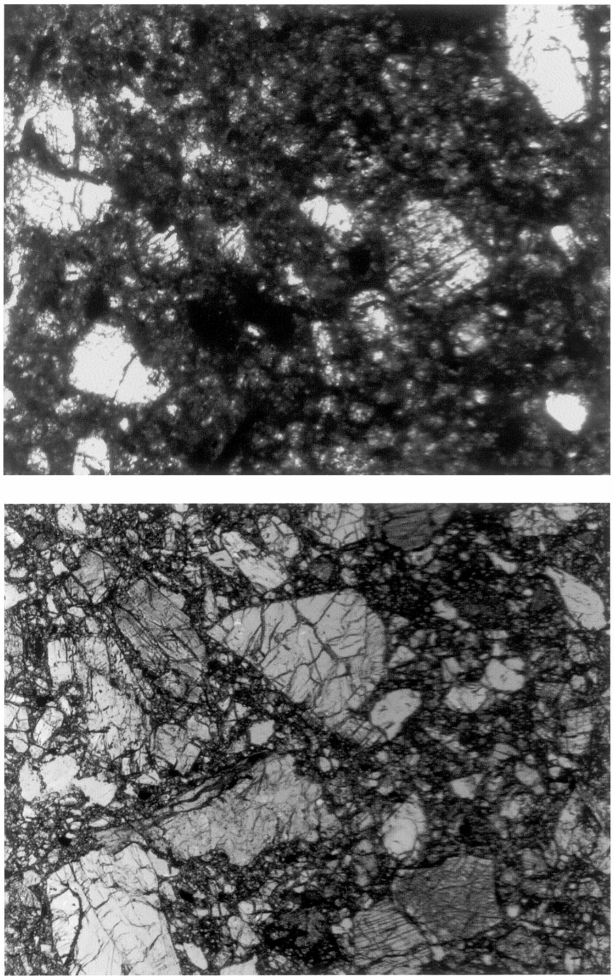

Fig. 1. Photomicrographs taken with plane-polarized light of the matrix of a) EET 87503 and b) EET 87513. Long axes of both photos are 1.8 mm.

Many of the HED meteorites have also experienced significant amounts of metamorphism. Based on pyroxene zoning patterns and exsolution textures, Takeda *et al.* (1976a, b) and Reid and Barnard (1979) divided eucrites into two groups: equilibrated and unequilibrated. Takeda and Graham (1991) refined this classification by noting a continuum of metamorphic grades ranging from type 1 (unequilibrated) to type 6 (most metamorphosed). An additional complication to determining the types of eucritic components in some howardite breccias is the partial equilibration of finer matrix mineral grains by metamorphism after mixing (Labotka and Papike, 1980; Fuhrman and Papike, 1981; Yamaguchi *et al.*, 1994, 1996; Metzler *et al.*, 1995). In this respect, EET 87503 and EET 87513 are appropriate as choices for analogues for the surface of 4 Vesta, because they have undergone minimal amounts of metamorphism after final aggregation (Buchanan, 1995).

EET 87503 and EET 87513 are also distinctive because they contain significant proportions of medium-sized to large clasts. Studies of these lithic clasts can provide more detailed information on the lithologic diversity and petrologic characteristics of the source rocks that were broken apart and mixed into these breccias (see also Bunch, 1975 and Ikeda and Takeda, 1984). The present study estimates the types of eucritic and diogenitic materials that were mixed together to form these breccias based on examination of twenty four lithic clasts and a large number of matrix mineral fragments. The goal of this study is to develop a model for the regolith of 4 Vesta.

2. Sampling and analytical techniques

Samples of EET 87503 and EET 87513 were extracted in the Meteorite Processing Laboratory at NASA JSC. Matrix samples, free from fusion crust or exterior surfaces, were separated from different parts of each meteorite and prepared as polished thin sections at JSC. Total area of the three matrix thin sections of EET 87513 that were examined for this study is ~75 mm^2. The two matrix thin sections of EET 87503 have a total area of ~100 mm^2. Clast fragments with adhering matrix were prepared as polished thin-sections for petrographic and microprobe analysis and clast materials free from adhering matrix or fusion crust were prepared for geochemical analysis. The samples were analyzed in two separate consortium studies organized by D.W. Mittlefehldt and J.C. Laul, respectively. Mittlefehldt and Lindstrom (1991a), Buchanan *et al.* (1990), and Buchanan and Reid (1991) reported preliminary data for some of the samples discussed here.

Mineral compositions were determined using the Cameca CAMEBAX and SX-100 electron microprobes at JSC and the JEOL JXA-8800M Superprobe at NIPR. The microprobes were operated at a voltage of 15 keV and a sample current of 20 nA or 30 nA with counting times for individual elements ranging from 20–40 s for major elements and 30–100 s for minor elements. Natural and synthetic standards were used and corrections were made for absorption, fluorescence, and atomic number effects using Cameca and JEOL on-line programs. Diameter of the electron beam was ~1 μm and was adequate to resolve all but the most fine-grained mineral fragments in the matrix.

Bulk samples of clasts and matrix were analyzed by instrumental neutron activation analysis (INAA) at JSC and at Oregon State University (OSU). Data for samples analyzed at OSU by Dr. Y.-G. Liu were acquired using techniques described in Liu and Schmitt (1990) and Laul (1979). The procedure consisted of two irradiations in the TRIGA reactor at Oregon State University. A short irradiation was performed in the pneumatic facility for 5 min at a neutron flux of 4.5×10^{11} $ns^{-1}cm^{-2}$ and counted for short half-life (minutes) nuclides. For the long irradiation, samples were activated for 7 hours at a neutron flux of 3×10^{12} $ns^{-1}cm^{-2}$ and counted for intermediate and long half-life nuclides. Activated samples were counted on both GeLi (100 cm^3 volume with 1.79 keV resolution and 19.3% efficiency for the 1.33 MeV ^{60}Co gamma-ray) and 5 mm thick planar intrinsic Ge (640 eV resolution for the 122 keV gamma-ray) detectors. The latter were used to obtain better Ce-141 (145.4 keV) and Nd-147 (91.1 keV) data.

Data for samples analyzed at JSC were acquired in two runs using the procedures detailed in Mittlefehldt and Lindstrom (1991b) and Mittlefehldt *et al.* (1992). Irradiations were performed at the Research Reactor Facility of the University of Missouri. In the first run, samples were irradiated for 20 hours at a flux of ~$5.5\times10^{13}\,ns^{-1}cm^{-2}$. In the second run, samples were irradiated for 12 hours at a similar flux.

3. Data

We define the clastic matrix of an HED meteorite as being composed of fragments of single crystals that, in most cases, comprise the largest volumetric proportion of these regolith breccias. In contrast, clasts are rock fragments that are usually composed of more than one crystal and for eucritic materials, more than one mineral. Clasts that represent volcanic and igneous rocks provide information about compositions of co-existing mineral phases and varying amounts of information about original rock textures, depending on the size of the clast relative to its grain size. The clasts analyzed in this study are rock fragments that are large enough (commonly greater than 5 mm in diameter) to provide significant amounts of textural and mineralogical information and, in some cases, provide enough material for INAA and isotopic analyses. The terms 'equilibrated' and 'unequilibrated' are used in this manuscript in a qualitative sense to describe clasts with textures that indicate high levels of equilibration (~types 4 to 6 of Takeda and Graham, 1991) or low levels of equilibration (~types 1 to 3 of Takeda and Graham, 1991), respectively.

A. Matrix—The compositions of matrix pyroxenes in EET 87503 and EET 87513 are plotted in Figs. 2a and 2b, and of matrix feldspars in Figs. 3a and 3b. A variety of diogenitic and eucritic materials are present. Pyroxenes range from magnesian orthopyroxenes similar in composition to those found in diogenites, to equilibrated pyroxenes similar to those found in Nuevo Laredo-trend eucrites. Also included are metastable Fe-rich pyroxenes similar in composition to the outer edges of zoned pyroxenes in unequilibrated eucrites (*e.g.,* Pasamonte). Among these matrix materials are fragments of pyroxenes that are compositionally similar to those in the cumulate eucrites Moore County and Binda (Ishii and Takeda, 1974; Takeda *et al.*, 1979). Feldspar fragments in EET 87503 and EET 87513 display a range of anorthite-rich compositions.

B. Clasts—Table 1 lists the twenty four clasts studied and their classification. We will refer to these clasts using a three digit meteorite identifier and a clast designation; that is, 503-G is clast G from EET 87503. Bulk compositions of clasts from EET 87513 are presented in Table 2, and from EET 87503 in Table 3.

Diogenites—Three clasts are predominantly composed of magnesian orthopyroxenes, similar in composition to those found in diogenites. These clasts have been deformed to varying degrees. Clast 503-D is mildly deformed with orthopyroxenes displaying undulating extinction and incipient mosaicism. Clasts 513-A/EE and 513-9 are fragments of diogenites that were brecciated and later recrystallized (Fig. 4). These two breccias are much finer-grained than typical brecciated diogenites and are similar to some fine-grained, recrystallized Yamato Type A (Y-74013-type) diogenites described by Takeda *et al.* (1975, 1978). Equant, anhedral orthopyroxene grains (<0.45 mm in size) are surrounded by a finer-grained (average grain size ~0.1

mm) matrix composed of equant orthopyroxene grains, minor olivine (Fo_{66}), and very small troilite grains. The limited range of pyroxene compositions (average Wo_1En_{74}) matches diogenitic orthopyroxenes (Fig. 5). The mineral grains composing these clasts are intergrown and were recrystallized after a brecciation event.

Bulk composition of clast 513-A/EE is listed in Table 2. Rare earth element (REE) abundances (Fig. 6a) are 1–2×CI and are somewhat higher than those of the diogenite Johnstown (Mittlefehldt, 1994). Europium is below the detection limit. The composition of this clast displays a small positive Ce anomaly. Mittlefehldt and

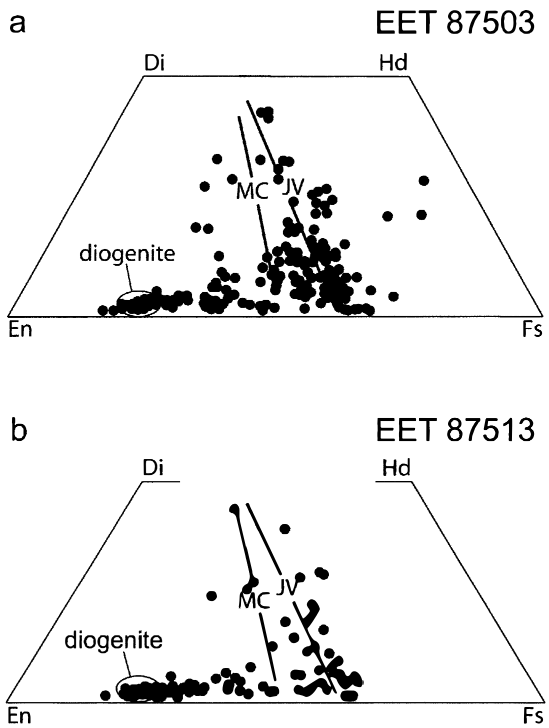

Fig. 2. Spectra of compositions of matrix pyroxenes in a) EET 87503 and b) EET 87513. Compositions of diogenitic pyroxenes and low-Ca and high-Ca pyroxenes from Juvinas (JV) and Moore County (MC) are from Basaltic Volcanism Study Project (1981).

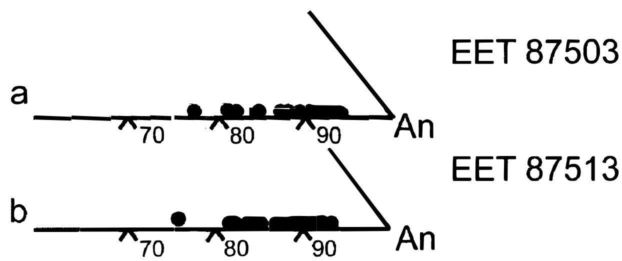

Fig. 3. Spectra of compositions of matrix feldspars in a) EET 87503 and b) EET 87513.

Table 1. List of clasts from EET 87503 and EET 87513 considered in this study and a brief petrologic classification of each.

EET 87503	
503-B	shocked, equilibrated Nuevo Laredo-trend eucrite
503-C	impact-melt breccia
503-D	diogenite
503-E	impact-melt breccia
503-F	equilibrated main-group eucrite
503-G	impact-melt breccia
503-L	equilibrated Nuevo Laredo-trend eucrite
503-M	brecciated Nuevo Laredo-trend eucrite
503-N	equilibrated main-group eucrite breccia
503-Z	main-group eucrite
503-BA	Nuevo Laredo-trend eucrite
503-BB	equilibrated main-group eucrite
503-BC	equilibrated polymict breccia
EET 87513	
513-A(EE)	brecciated, metamorphosed diogenite
513-B	Nuevo Laredo-trend eucrite
513-E	unequilibrated main-group eucrite
513-N	CM2
513-X	Binda-type pyroxene
513-Y	cumulate eucrite-related
513-5	cumulate eucrite-related
513-6	polymict breccia
513-7	CM2
513-8	equilibrated, shocked polymict breccia
513-9	brecciated, metamorphosed diogenite

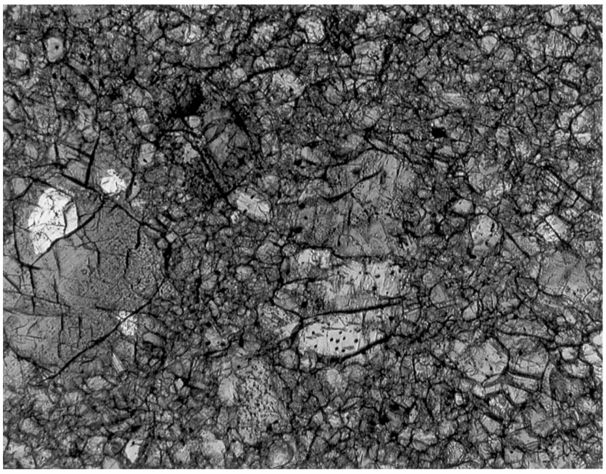

Fig. 4. Photomicrograph of diogenitic breccia clast 513-A/EE. Long axis of the photo is 1 mm.

Table 2. Compositions acquired by INAA for clasts from EET 87513. Some data were previously reported in Buchanan (1995).

	513-A/EE	513-B	513-E	513-Y	513-5	513-7
curatorial sample #	,23	,25	,76	,35	,109	,118
location	OSU	OSU	OSU	OSU	JSC	JSC
wt.(mg)	38.7	42.8	34.7	59.2	50.3	9.11
type	diogenite	eucrite	eucrite	eucrite	eucrite	CM2
wt. %						
TiO_2	n.d.	0.54	n.d.	n.d.	n.d.	n.d.
Al_2O_3	n.d.	11.9	13.5	16.0	n.d.	n.d.
Cr_2O_3	0.902	0.343	0.447	0.358	0.393	0.469
FeO	17.6	23.6	18.5	10.4	17.4	27.9
MnO	0.57	0.3	0.59	0.37	n.d.	n.d.
CaO	0.91	10.4	11.3	10.6	8.8	1.5
Na_2O	0.0152	0.54	0.37	0.197	0.259	0.228
K_2O	n.d.	0.065	0.036	0.0094	n.d.	n.d.
ppm						
Sc	12.5	36.4	29.8	13.9	26.0	7.98
V	134	78	n.d.	99	n.d.	n.d.
Co	21.4	4.7	9.8	9.6	12.1	590
Ni	55	42	28	21	37	12400
Sr	n.d.	106	91	73	59	n.d.
La	0.33	2.91	2.67	0.20	0.689	0.597
Ce	1.6	7.3	6.6	0.73	2.54	1.7
Nd	n.d.	n.d.	5.6	n.d.	n.d.	n.d.
Sm	0.149	1.97	1.84	0.284	0.637	0.322
Eu	n.d.	0.69	0.57	0.30	0.385	0.089
Tb	n.d.	0.62	0.49	0.09	0.20	0.08
Dy	n.d.	3.9	4.4	n.d.	n.d.	n.d.
Yb	0.21	2.1	1.70	0.18	0.99	0.32
Lu	0.039	0.44	0.26	0.019	0.149	0.052
Hf	n.d.	1.5	1.16	n.d.	0.55	n.d.
Ta	n.d.	0.21	0.15	n.d.	0.04	n.d.
Th	n.d.	0.38	0.51	n.d.	n.d.	n.d.
ppb						
Au	n.d.	2.2	4.4	2.3	n.d.	246

n.d.=not determined

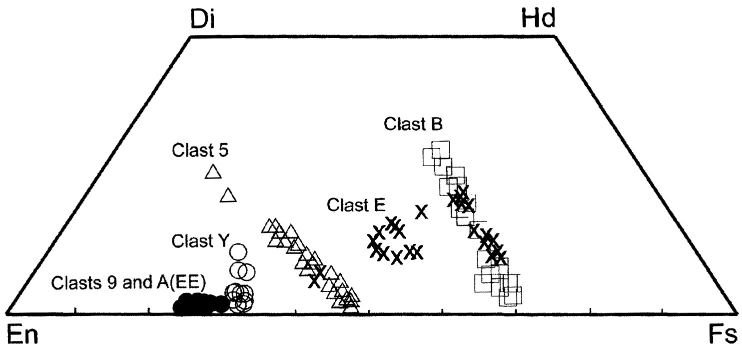

Fig. 5. Compositions of pyroxenes in clasts in EET 87513.

Table 3. Compositions acquired by INAA for clasts from EET 87503.

	503-F	503-L	503-M	503-Z	503-BA
curatorial sample #	,136	,109	,105	,116	,122
location	JSC	JSC	JSC	JSC	JSC
wt.(mg)	55.2	46.2	40.7	77.1	62.4
type	eucrite	eucrite	eucrite	eucrite	eucrite
wt. %					
Cr_2O_3	0.315	0.283	0.300	0.292	0.369
FeO	19.2	20.0	19.9	18.4	18.1
MnO	0.57	0.3	0.59	0.37	n.d.
CaO	9.7	10.0	10.0	10.3	10.1
Na_2O	0.429	0.626	0.501	0.473	0.480
K_2O	n.d.	n.d.	n.d.	n.d.	0.042
ppm					
Sc	30.8	33.7	29.8	30.8	29.4
Co	5.47	6.25	4.00	3.42	12.2
Ni		40			40
Sr	70	90	90	80	100
La	1.84	4.11	3.35	2.21	3.47
Ce	5.2	10.5	9.0	6.0	10.7
Nd	4.0	5.0	6.0	5.0	6.0
Sm	1.27	2.58	2.09	1.50	2.26
Eu	0.54	0.75	0.69	0.65	0.68
Tb	0.32	0.62	0.52	0.40	0.55
Yb	1.62	2.50	2.04	1.84	2.17
Lu	0.246	0.363	0.304	0.270	0.315
Hf	0.93	1.88	1.45	1.24	1.86
Ta	0.082	0.24	0.17	0.21	0.34
Th	0.18	0.43	0.35	0.19	0.47
ppb					
Au	n.d.	n.d.	n.d.	n.d.	n.d.

n.d.=not determined

Lindstrom (1991b) reported abnormal trace element abundances, including positive Ce anomalies, for some Antarctic HED meteorites and attributed these anomalies to terrestrial weathering. Hence, the most reasonable interpretation for the composition of clast 513-A/EE is that REEs and, in particular, Ce were mobilized from the matrix of the meteorite into this clast by terrestrial weathering. In contrast, most of the other lithic clasts that were analyzed in this study underwent minimal terrestrial alteration.

Eucrites—A variety of eucritic clasts are present in EET 87503 and EET 87513. Clasts 513-Y and 513-5 are equilibrated igneous rocks and contain relatively magnesian pyroxene (Fig. 5) and anorthite-rich feldspar (Fig. 7). Clast 513-Y originally had a medium-grained texture and was subsequently deformed and extensively recrystallized. This clast has abundances of most REE of 0.9–2×CI with enrichment of Eu at 5×CI (Table 2, Fig. 6b). Clast 513-5 was also originally a medium-grained igneous rock and moderate metamorphism caused minor recrystallization of pyroxene and feldspar. The abundances of REE of this clast are similar to those of a cumulate eucrite, Moore County (Kitts and Lodders, 1998), at 3–6×CI for most REE with an enrichment of Eu at 6.9×CI (Table 2, Fig. 6b). These clasts probably represent fragments of cumulate

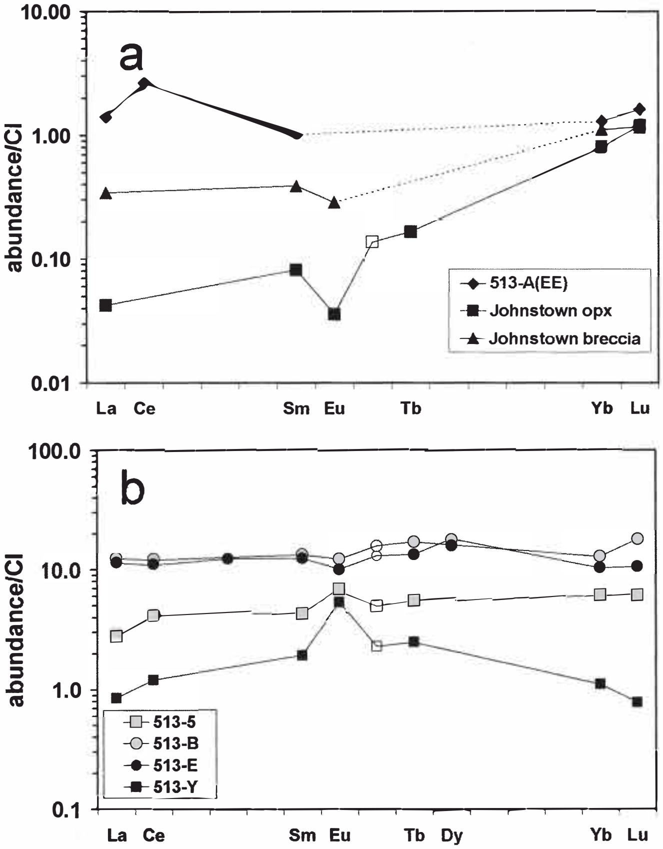

Fig. 6. Chondrite-normalized REE abundances of clasts in EET 87513. Abundances are normalized to the C1 composition of Anders and Grevesse (1989). Chondrite-normalized abundances of Gd (open symbols) are estimated by linear interpolation between chondrite-normalized abundances of Sm and Tb or Sm and Yb. a) diogenitic clast. b) eucritic clasts. The composition of Johnstown orthopyroxene and breccia are from Mittlefehldt (1994).

eucrite-like parent rocks. Clast 513-X represents a very large fragment (3×2 mm in thin section) of low-Ca magnesian pyroxene with blebby augite exsolution lamellae. This pyroxene is similar to the pyroxene in Binda described by Ishii and Takeda (1974) and Takeda *et al.* (1979) and probably is related to cumulate eucrites.

EET 87503 and EET 87513 also contain several eucritic clasts with subophitic textures. Clast 503-F (Fig. 8) is equilibrated and is composed of lath-shaped plagioclase and anhedral pyroxene without mesostasis. Pyroxene compositions (Fig. 9a) are slightly more Fe-rich than those of Juvinas (Basaltic Volcanism Study Project, 1981). Bulk composition is listed in Table 3; REE abundances (Fig. 10a) are flat at ~$10 \times$CI and are similar to those of Juvinas (Jérome, 1970). Hence, clast 503-F is a fragment of equilibrated, main-group eucrite. Clast 503-Z (composition: Table 3, Fig. 10a) is also a fragment of main-group eucrite.

Unequilibrated eucrite clasts also occur in both howardites. Clast 513-E contains

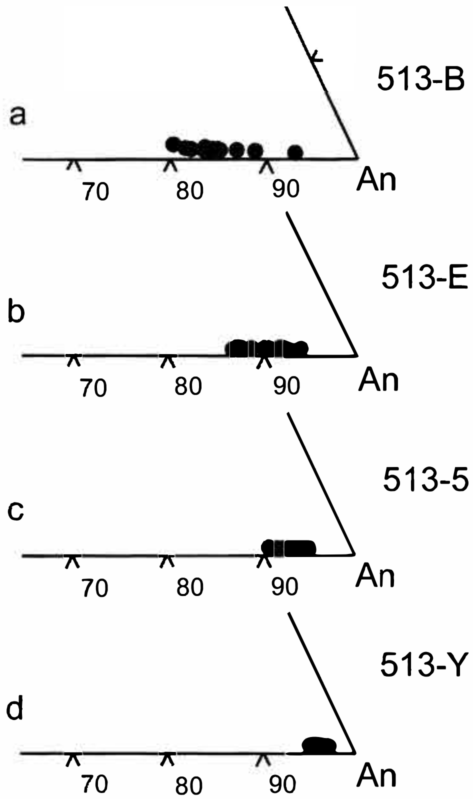

Fig. 7. Compositions of feldspars in clasts in EET 87513.

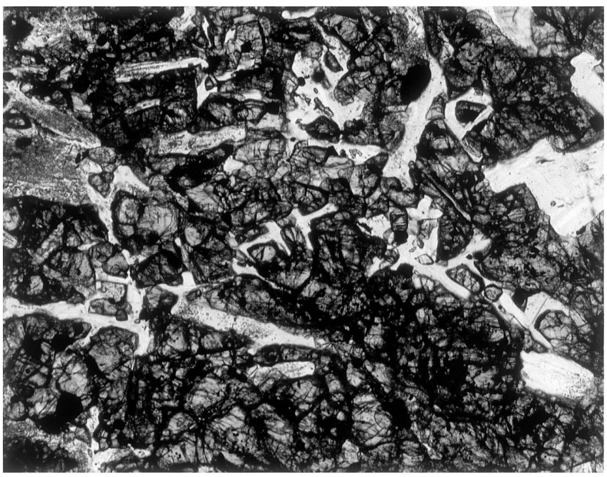

Fig. 8. Photomicrograph of clast 503-F. Long axis of the photo is 1.8 mm.

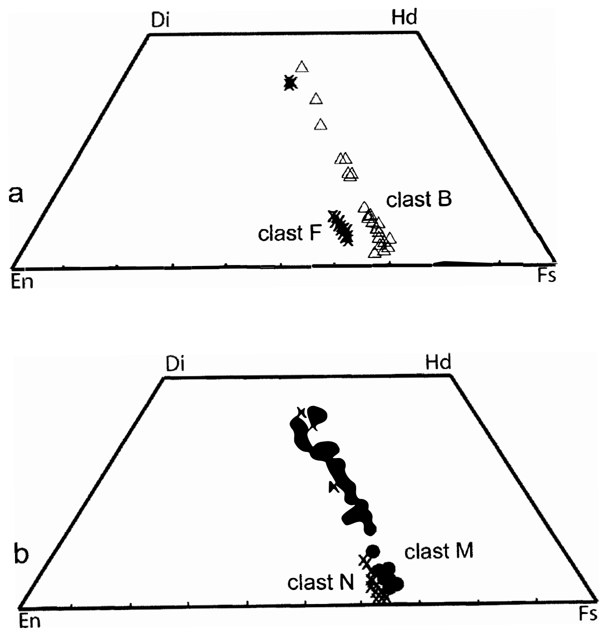

Fig. 9. Compositions of pyroxenes in clasts in EET 87503: a) clasts 503-F and 503-B, b) clasts 503-M and 503-N.

plagioclase and zoned pyroxene with compositions (Fig. 5) similar to those of Pasamonte (Basaltic Volcanism Study Project, 1981). The bulk composition of the clast (Table 2) has REE abundances of 10–13×CI with a relatively small depletion of Eu [$(Eu/Sm)_{CI}=0.81$] (Fig. 6b).

Fragments of evolved eucrites also occur in EET 87503 and EET 87513. Clast 513-B (composition: Table 3, Fig. 10a) is equilibrated with pyroxene compositions (Fig. 5) similar to those of Nuevo Laredo (Basaltic Volcanism Study Project, 1981). This clast is slightly enriched in REE relative to clast 513-E (Table 2) and has a slight Eu depletion of $(Eu/Sm)_{CI}=0.92$ (Fig. 6b). However, 513-B has lower abundances of LREE and Th than Nuevo Laredo (2.91 *vs.* 3.92 μg/g La; 380 *vs.* 466 ng/g Th), higher FeO content (23.6 *vs.* 19.4 wt%), and very similar abundances of Al_2O_3, CaO, HREE, Hf and Ta (Table 2 and Kitts and Lodders, 1998). The lower LREE and Th contents and similar HREE, Hf, and Ta contents can be explained by slight under-sampling of accessory phosphates in the available clast materials (43 mg). In contrast, the high FeO content could indicate over-sampling of pyroxene. However, the abundances of Al_2O_3 and CaO, which are similar to those of Nuevo Laredo, do not support under-sampling of feldspar and over-sampling of pyroxene, but instead suggest that the pyroxenes are more Fe-rich. An alternative interpretation is that substantial troilite, roughly 5 wt%, was contained in the INAA sample. It is unlikely that the high Fe content is due to metal, because even if this metal is the low Co, Ni metal present in some lithic clasts in howardites (Hewins, 1979), it would result in higher proportions of Co and Ni than measured for this clast (Table 2). Hence, clast 513-B is best interpreted as

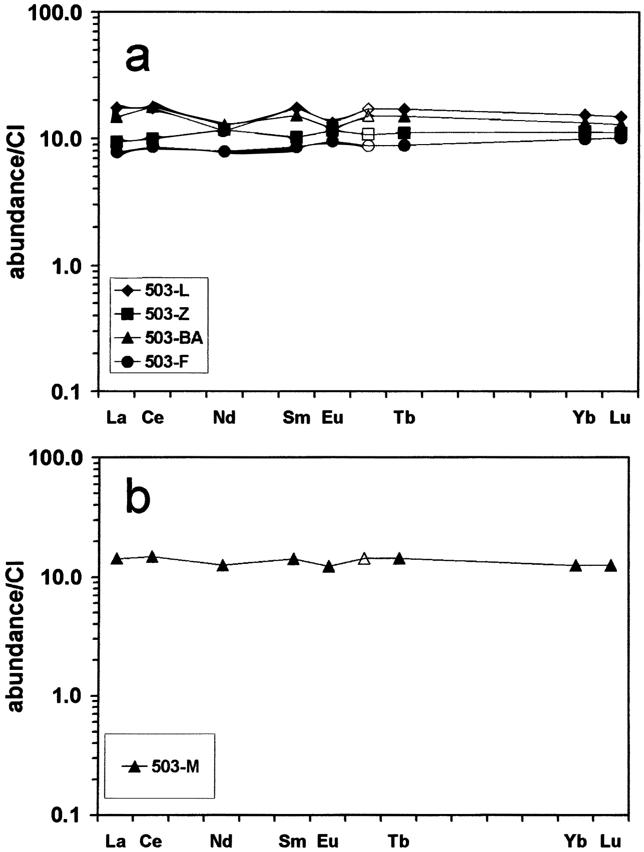

Fig. 10. Chondrite-normalized REE abundances of clasts in EET 87503. Abundances are normalized to the C1 composition of Anders and Grevesse (1989). Chondrite-normalized abundances of Gd (open symbols) are estimated by linear interpolation between chondrite-normalized abundances of Sm and Tb. a) eucritic clasts. b) breccia clast.

similar to, but more Fe-rich than, Nuevo Laredo. Clast 503-BA (composition: Table 3, Fig. 10a) is also a Nuevo Laredo-trend eucrite.

The variations in the isotopic systematics of individual lithic clasts in EET 87513 and EET 87503 indicate that these materials experienced different amounts of post-crystallization metamorphism before incorporation into these regolith breccias. Nyquist *et al.* (1992, 1994) dated the unequilibrated eucritic clast 513-E at ~4.5 Ga by Rb-Sr and Sm-Nd isotopic analysis and suggested that this was the age of initial crystallization. In contrast, EET 87503,53, an equilibrated eucritic clast originally described by Mittlefehldt and Lindstrom (1991a), was dated by Nyquist *et al.* (1994) as having a similar crystallization age as clast 513-E, but having isotopic systematics that were partially reset ~2.3–3.5 Ga ago by a metamorphic event that was probably related to impact.

Impact-modified materials—Impact-modified materials are also represented among clasts in EET 87503 and EET 87513. They include a variety of shocked eucrites, lithified eucrite and howardite clastic breccias, and impact-melt breccias. The spectrum of impact-modified clasts is reminiscent of those in the meteorite Kapoeta, which contains polymict breccia clasts and impact-melt breccia clasts (*e.g.,* Pun *et al.*, 1998). Among the eucritic clasts in EET 87503 and EET 87513, relatively unshocked eucrites form a continuous series with eucrites that experienced varying degrees of shock deformation. In some cases, eucritic clasts have pyroxenes that are blackened to varying degrees; clast 503-B is an example of one of these clasts. We suggest that this blackening of pyroxene is the result of shock, because these clasts commonly display other textural evidence (*e.g.,* undulating extinction and fracturing of minerals) consistent with shock. In some cases, these blackened pyroxenes may have been transformed into diaplectic glass by shock and later recrystallized to fine-grained aggregates, including abundant, very small opaque mineral grains. The presence of numerous blackened pyroxene grains in the matrices of these meteorites indicates that these shocked eucritic clasts are not anomalous materials. Clast 503-B has an ophitic/subophitic texture composed of skeletal feldspar and anhedral, blackened pyroxene with a large proportion of fine-grained mesostasis. Pyroxenes are equilibrated with a relatively constant Mg# of ~30 (Fig. 9a). Feldspars vary in composition from An_{74} to An_{89}.

Also included among these shock-related materials are fragments of lithified monomict and polymict breccias. Clast 503-M is a shocked breccia with blackened pyroxenes and REE abundances (Table 3) of ~12–15×CI with $(Eu/Sm)_{CI}$ of 0.87 (Fig. 10b). Pyroxene compositions of this clast are equilibrated with an average Mg# of ~40 (Fig. 9b). Feldspar compositions range from An_{81} to An_{93}. Hence, clast 503-M is a shocked breccia originally derived from eucritic material similar to Nuevo Laredo (Warren and Jerde, 1987). Clast 503-N is another breccia composed of equilibrated material and contains pyroxene with an average Mg# of ~39 (Fig. 9b). Clasts 513-6 and 513-BC are polymict breccias and include pyroxenes with a wide range of compositions. Clast 513-8 has a limited range of magnesian pyroxene compositions and a texture that suggests extensive post-brecciation metamorphism. This clast also displays evidence of extensive shock, including blackened pyroxenes.

Several clasts are fragments of impact-melt breccias similar to those described by Pun *et al.* (1998). These breccias are composed of fragments of silicate minerals in a dark, almost opaque groundmass that is probably devitrified glass (Fig. 11). Clasts 503-G, 503-C, and 503-E, as well as numerous small lithic fragments in the matrix of both meteorites, represent these materials. Mittlefehldt and Lindstrom (1991a) described similar clasts and indicated that they are generally similar in composition to howardites with low Ca and Sc and high Cr. Composition of the glassy matrix of clast 503-G acquired by defocused beam microprobe analysis is generally eucritic.

Non-HED materials: Carbonaceous chondrites—A carbonaceous chondrite clast, 513-N, was previously described and classified as CM2 (Buchanan *et al.*, 1993). Clast 513-N is composed of coarser-grained anhydrous silicates in a finer-grained, opaque matrix. This matrix is predominantly composed of sulfides (pyrrhotite and pentlandite) and phyllosilicates, including serpentine and minor saponite, and has a flowing texture similar to that of CM2 matrices. The bulk oxygen isotopic composition of this clast is consistent with classification as CM2 material. Bulk trace element

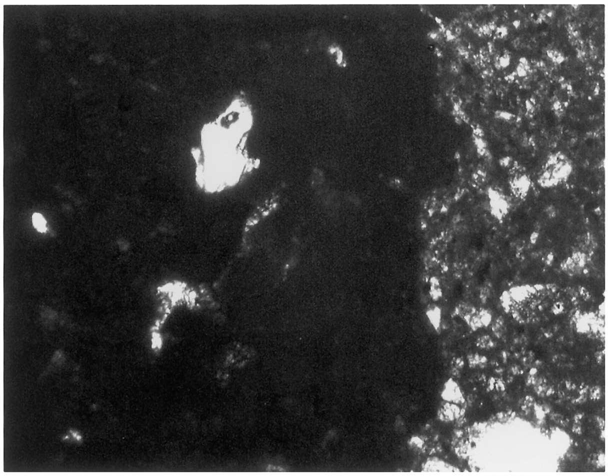

Fig. 11. Photomicrograph of clast 503-C, an impact-melt breccia. Clast is on the left ; matrix of EET 87503 is on the right. Long axis of the photo is 1.8 mm.

abundances acquired by INAA and bulk major element abundances acquired by defocused beam microprobe analysis also are generally consistent with classification as CM2 material. Basal lattice fringes of the groundmass serpentine grains in clast 513-N are corrugated and suggest thermal metamorphism affected the clast (Buchanan *et al.*, 1993).

A second carbonaceous chondrite clast, 513-7, is also a CM2 fragment. Texture and mineralogy of the fine-grained matrix of this clast is similar to that of 513-N. Bulk composition is listed in Table 2. Abundances of most elements are 1–2×CI, except Na at 0.34×CI. This composition is also broadly consistent with identification as a carbonaceous chondrite, although Na is anomalous.

4. Discussion

Characterization of the regolith—The proportions of diogenitic and eucritic materials in these regolith breccias can be roughly estimated by considering random analyses of matrix pyroxenes. For this study, we have assumed that a random sample will result from analyzing most of the pyroxene grains $>5\,\mu$m in size in several selected areas of the meteorite matrix. Hence, we assume that there is no difference in the spectrum of original pyroxene compositions among the very fine-grained ($<5\,\mu$m in size) pyroxenes and those that are large enough to be analyzed by electron microprobe. For this study, pyroxenes with Mg# >70 are assumed to be derived from diogenites and those with Mg# <70 from eucrites. Further, eucritic materials are assumed to be composed of subequal proportions of pyroxene and plagioclase. Hence, based on these assumptions, a statistically significant number of random analyses of matrix pyroxenes can be used to estimate the approximate volumetric proportions of diogenitic versus eucritic materials in an HED polymict breccia. Volumetric proportions are also assumed to approximate weight proportions, because diogenites (~3.3 g/cm^3) and eucrites (~3.1 g/cm^3) differ in density by only ~5–10% (*e.g.* Wasson, 1974).

Using this methodology, EET 87503 contains 17 wt% diogenitic material. Based on bulk compositional data, Mittlefehldt and Lindstrom (1991a) made a similar estimate of 20 wt% diogenitic material in EET 87503. In contrast, based on matrix mineral compositions, EET 87513 contains 22 wt% diogenitic material. Mittlefehldt and Lindstrom (1991a) estimated that EET 87513 contains 35 wt% diogenitic material. This range in proportions of diogenitic and eucritic materials is reasonable for different samples of the same regolith breccia, and these meteorites are both howardites (Delaney *et al.*, 1983). Bulk compositions of brecciated matrix samples of EET 87513 are listed in Table 4.

Table 4. Bulk composition of the matrix of EET 87513 acquired by INAA at Oregon State University.

	Sample 1	Sample 2	Sample 3	weighted average
curatorial sample #	,48	,50	,56	
wt.(mg)	58.2	69.8	66.8	
TiO_2	0.42	0.50	0.36	0.43
Al_2O_3	7.2	9.2	8.6	8.4
Cr_2O_3	0.741	0.737	0.808	0.763
FeO	18.7	19.5	18.9	19.1
MnO	0.55	0.53	0.52	0.53
CaO	6.6	7.5	6.7	7.0
Na_2O	0.258	0.33	0.31	0.30
K_2O	0.024	0.029	0.026	0.026
ppm				
Sc	22.8	26.5	24.6	24.7
V	101	98	104	101
Co	37.	18.3	29.7	27.8
Ni	278	145	403	273
Sr	46	63	59	57
La	1.63	2.03	2.02	1.91
Ce	5.1	5.8	4.4	5.1
Nd	n.d.	4.8	n.d.	n.d.
Sm	1.12	1.34	1.38	1.29
Eu	0.34	0.43	0.40	0.39
Tb	0.29	0.38	0.35	0.34
Dy	1.9	2.0	1.4	1.8
Yb	0.98	1.23	1.19	1.14
Lu	0.16	0.21	0.19	0.19
Hf	0.80	0.94	0.90	0.88
Ta	0.11	0.15	0.10	0.12
Th	0.16	0.30	0.25	0.24
ppb				
Ir	10	5.0	12	9
Au	6.3	1.7	5.0	4.2
ratios				
Ir/Ni	3.6×10^{-5}	3.4×10^{-5}	3.0×10^{-5}	3.3×10^{-5}
Au/Ni	2.3×10^{-5}	1.2×10^{-5}	1.2×10^{-5}	1.5×10^{-5}
Co/Ni	0.133	0.126	0.074	0.102

n.d.=not determined

Is it possible to determine the relative proportions of different types of eucritic materials in these regolith breccias? As discussed above, this is difficult using only matrix mineral compositions, because, in some cases, different petrologic types of eucrites have similar mineral compositions. However, petrologic information is available for a significant number of clasts from EET 87503 and EET 87513. Can we use the relative proportions of the different types of clasts to clarify the eucritic components in these breccias? The grain size of the original material must be considered. For example, roughly 12% of the clasts studied from these breccias are diogenites, compared to an estimated 17% and 22% diogenitic components for EET 87503 and EET 87513, respectively, based on compositions of matrix pyroxene fragments. One explanation for this discrepancy is the original pre-brecciation grain size of diogenitic materials. Because most diogenites originally represented coarse-grained igneous rocks, a fragment must be very large to contain more than one mineral grain and, thus, fit our definition of lithic clast. Hence, except for the fine-grained brecciated and recrystallized diogenites 513-A/EE and 513-9, most diogenitic materials in these meteorites would be considered as part of the matrix.

For similar reasons, carbonaceous chondrite clasts are over-represented among clasts. In this case, ~8% $(=(2/24)\times 100\%)$ of the clasts studied in EET 87503 and EET 87513 are carbonaceous chondrites. As discussed below, geochemical data suggest that there is a much smaller proportion of carbonaceous chondrite material in these breccias. The fine-grained texture of these materials results in even very small fragments being classified as clasts. Small fragments are also easily distinguishable in thin section. In addition, the dark color of the carbonaceous chondrite and impact-melt materials causes them to stand out in hand samples and makes them obvious targets for extraction.

There may also be a selection bias. Clasts that appeared very similar to other clasts in hand sample may not have been selected for extraction. However, a random sampling of matrix grains should provide a closer approximation to mixing ratios of diogenitic and eucritic parent materials than clast samples, and this appears to be true in this case; our estimated diogenitic content based on matrix pyroxene compositions is generally close to that estimated from bulk compositions of matrix samples. In contrast, relative proportions of different types of eucritic materials among clasts are probably closer to the actual relative proportions of these materials in the breccias, because these materials are generally intermediate in grain size.

Considering the above factors, we can develop a geochemical model for these breccias. We initially assume that the diogenitic component in EET 87513 is 22 wt% as suggested by the spectrum of matrix pyroxene compositions. Based on the work of Chou *et al.* (1976), we further assume a component of CM2 material of 2 wt%, which is generally consistent with Ni and Co abundances for EET 87513 presented in Table 4. The remaining 76 wt% of the mixture is assumed to have proportions of the various types of eucrites and polymict materials close to those represented among the lithic clasts. For example, 5 of the 19 eucritic and polymict clasts considered in this study are main-group eucrites. Hence, 20 wt% $(=(5/19)\times 76\,\text{wt}\%)$ of the mixture was assumed to be main-group eucrite. We have not attempted to make our estimates based on the actual size or weights of the individual clasts; instead, we have exclusively used numbers of different types of clasts to calculate these proportions. Based on this methodology, a reasonable estimate, by weight, based on the data presented in Table 1 includes 22% diogenite, 20% main-group eucrite, 20% evolved eucrite, 12% cumulate eucrite, 24% polymict material, and 2% CM2. We have classified polymict and impact-melt breccia clasts as polymict materials. There is no evidence among the twenty four clasts analyzed in this study, and, in particular, among the eleven clasts analyzed by INAA, for the presence of Stannern-trend eucrite material in these breccias, and we excluded it as a component. The character of this mixture is probably related to the depth of excavation by impact processes on 4 Vesta.

It must be noted, however, that some of the eucritic materials in EET 87503 and EET 87513 are not similar to any materials previously documented as individual meteorites. For example, some eucritic clasts have bulk compositions that are typical of different types of eucrites, but have blackened pyroxenes. There are also several clasts that represent impact-melt breccias. The presence of large proportions of these shocked clasts suggests that a large proportion of the matrix mineral fragments may have experienced complicated histories. There is also further evidence (see description of clast 513-B above) for a component of eucritic material that is more Fe-rich than Nuevo Laredo in these breccias.

Modeling—Based on the above estimate of the various petrologic types of HED materials contained in EET 87513, a model composition (model 1 in Table 5) was calculated. For this calculation, compositions of geochemically well-characterized eucrites, diogenites, and howardites were chosen to represent different types of HED materials. These end members seem reasonable, because they are generally similar to the different groups of materials represented among HED meteorites. Juvinas was chosen as an analogue for main-group eucrites, Moore County for cumulate eucrites, and Nuevo Laredo for evolved eucrites. Johnstown and Tatahouine were chosen for diogenites. Compositions of Juvinas, Nuevo Laredo, and Moore County were taken from Kitts and Lodders (1998) and compositions of Johnstown and Tatahouine from Mittlefehldt (1994) and Jérome (1970). We used Murchison (composition: Kallemeyn and Wasson, 1981; Blichert-Toft and Albarède, 1997) as a typical CM chondrite in the model.

Chaves was chosen to represent clasts of polymict breccias and impact-related materials, because it is intermediate in composition in the range of materials represented by howardites and polymict eucrites. For example, abundance of Al_2O_3 for Chaves is 9.67 wt% (Jérome, 1970) compared with those of the polymict eucrites Macibini (12.2 wt%; Jérome, 1970) and EETA 79011 (11.4 wt%; Palme *et al.*, 1983) and the howardites Washougal (6.70 wt%; Jérome, 1970) and Pavlovka (7.64 wt%; Jérome, 1970). Abundance of La for Chaves is 2.17 ppm (Jérome, 1970) compared with those of the polymict eucrites Macibini (3.23 ppm; Jérome, 1970) and EETA 79011 (3.01 ppm; Palme *et al.*, 1983) and the howardites Washougal (1.38 ppm; Jérome, 1970) and Pavlovka (1.32 ppm; Jérome, 1970). Hence, the composition of Chaves is probably close to an average of the compositions of polymict breccias of the HED meteorite suite.

The composition of model 1 is generally similar to the bulk composition of EET 87513 (Table 5). The lower abundances of FeO for the model compared to EET 87513 may be the result of too small a proportion of Nuevo Laredo in this mixture or may result from a eucritic component that is more Fe-rich than Nuevo Laredo. The abundance of CM2 material is consistent with the more general result, based on siderophile element data, that a carbonaceous chondrite component typically ranges from 2.4 to 3.3% in some howardites and polymict eucrites (Chou *et al.*, 1976). However, the proportion of CM2 material in EET 87513 is somewhat surprising because thin section examination does not suggest such a large proportion of chondritic debris in these breccias. Possibly, much of the CM2 material is present as sub-microscopic particles between individual mineral and lithic fragments in the matrix. Gounelle *et al.* (1999) described small carbonaceous chondrite fragments in some HED polymict breccias. Very small particles would be difficult to recognize by optical microscopy. This suggests that much of this CM2 material may have been incorporated into the

Table 5. Compositions of HED and CM2 meteorites and the calculated model compositions discussed in the text.

	diogenite	Juvinas	Nuevo Laredo	Moore County	Chaves	Murchison	model 1	model 2	model 3	EET 87513 avg.
wt %										
TiO_2	0.04	0.62	0.87	0.37	0.40	0.17	0.45	0.45	n.d.	0.43
Al_2O_3	0.50	13.1	12.0	14.7	9.67	2.67	9.27	9.00	n.d.	8.4
Cr_2O_3	0.97	0.26	0.28	0.39	0.51	0.51	0.50	0.51	0.54	0.763
FeO	14.3	17.9	19.4	14.8	17.1	30.0	17.1	17.0	18.5	19.1
CaO	0.83	10.7	10.3	10.3	7.71	2.30	7.52	7.32	7.57	7.0
Na_2O	0.01	0.43	0.52	0.42	0.33	0.26	0.33	0.32	0.27	0.30
K_2O	b.d.	0.04	0.05	0.02	0.04	0.03	0.03	0.03	n.d.	0.026
ppm										
Sc	11.9	28.0	38.6	22.5	20.6	9.30	23.8	24.3	22.9	24.7
V	140	85	61	92	110	78	99	96	n.d.	101
Co	18.4	4.7	2.1	5.0	23.7	628	24.3	26.9	30.5	27.8
Ni	20.0	4	3	12	39.0	13500	287	415	n.d.	273
Sr	<5	74.9	82.8	71	42.0	12.5	51.5	53.4	n.d.	57
La	0.082	2.58	3.92	1.16	2.17	0.41	1.99	1.86	1.54	1.91
Sm	0.057	1.62	2.26	0.89	1.35	0.46	1.23	1.15	1.06	1.29
Eu	0.013	0.62	0.74	0.57	0.39	0.08	0.44	0.44	n.d.	0.39
Yb	0.18	1.60	2.36	1.00	0.82	0.25	1.15	1.22	1.05	1.14
Lu	0.029	0.26	0.32	0.20	0.20	0.02	0.19	0.19	0.19	0.19
Hf	0.05	1.3	1.61	0.61	0.92	0.13	0.89	0.85	n.d.	0.88

b.d. = below detection limits
n.d. = not determined

The model 1 composition is based on a mixture, by weight, of 22% diogenite + 20% Juvinas + 20% Nuevo Laredo + 12% Moore County + 24% Chaves + 2% Murchison.

The model 2 composition is based on a mixture, by weight, of 30% diogenite + 25% Juvinas + 25% Nuevo Laredo +17% Moore County + 3% Murchison. Composition of Murchison is from Kallemeyn and Wasson (1981) and Blichert-Toft and Albarède (1997). Composition of Chaves is from Jérome (1970). Compositions of Juvinas, Nuevo Laredo, and Moore County are from Kitts and Lodders (1998). The diogenite composition is a mixture of data for Johnstown and Tatahouine from Mittlefehldt (1994) and Jérome (1970).

The model 3 composition is based on a mixture, by weight, of 30% clast 513-A/EE + 25% clast 513-E + 25% clast 513-B + 17% clast 513-Y + 3% clast 513-N (Buchanan *et al.*, 1993).

regolith as very fine debris resulting from the impacts of CM2 meteorites on the surface of the HED parent body, or possibly as accreted interplanetary dust.

Elevated abundances of Ni and Co in HED breccias are not always the result of contamination by chondritic materials. For example, the polymict eucrite Petersburg contains relatively high abundances of Ni and Co (Buchanan and Reid, 1996), which result from large Fe/Ni metal grains in the matrix (see Duke, 1965; Hewins, 1979). Several other HED meteorites, including Yurtuk and Malvern, also contain significant proportions of matrix metal, and it is not always clear whether this metal is foreign or indigenous (Hewins, 1979). However, examination of matrix thin sections of EET 87503 and EET 87513 located only a few metal grains, which were too small to analyze by electron microprobe. There is also no evidence for rusty patches, indicating oxidation of Fe/Ni metal in the terrestrial atmosphere, on samples of these breccias. Rusty patches are quite common on samples of metal-rich howardites (*e.g.,* Petersburg). Most of the opaque mineral grains in EET 87503 and EET 87513 are ilmenite, chromite, or sulfide. Thus, the high Ni and Co contents are most likely due to CM chondrite debris.

Model 1 includes 24 wt% polymict material, which is, after all, a mixture of basaltic, gabbroic, orthopyroxenitic and chondritic parent materials. Therefore, we computed a second model using only these components (model 2, Table 5). This model was calculated by excluding the polymict material and normalizing the remaining components to 100%. Proportions were rounded off, except for the cumulate eucrite and CM2 materials, to the nearest 5 wt%. Model 2 included, by weight, 30% diogenite, 17% cumulate eucrite, 25% main-group eucrite, 25% Nuevo Laredo-trend eucrite, and 3% CM2 chondrite. The results of this model are listed in Table 5 and are generally similar to those of model 1 and to the bulk composition of EET 87513. We also computed a third model (model 3, Table 5) with the same proportions of components as model 2, but using compositions of 'local' components. Composition of clast 513-A/EE was chosen to represent diogenitic material and compositions of clasts 513-E, 513-B, and 513-Y were chosen for main-group, evolved, and cumulate eucrite materials, respectively. Composition of clast 513-N (Buchanan *et al.*, 1993) was chosen to represent CM2 material. Although compositional data for some of these materials is limited, model 3 is much closer to the average composition of EET 87513 than the other models. This suggests that EET 87513 contains a significant amount of evolved eucritic material that is more Fe-rich than Nuevo Laredo and is similar to clast 513-B.

We found no evidence for Stannern-trend eucritic material in EET 87503 and EET 87513. Its absence is problematical for meteorites that might be considered to be analogues for portions of the regolith of 4 Vesta. However, although incompatible element-rich eucritic clasts previously have been documented in polymict eucrites and howardites (*e.g.,* Mittlefehldt, 1979; Buchanan and Reid, 1996), these materials are relatively rare. The reflectance spectra data (*e.g.* Hiroi *et al.*, 1994) are unlikely to distinguish among main-group and Stannern-trend materials, because pyroxene compositions are similar.

5. Conclusions

1) EET 87503 and EET 87513 contain fragments of a wide variety of HED materials, including diogenites, eucrites, and various types of impact breccias. Among the eucritic clasts are cumulate eucrites, main-group eucrites, and evolved (Nuevo Laredo-type) eucrites. The non-cumulate eucrites include examples with unequilibrated and equilibrated textures. We did not find any incompatible element-rich, Stannern-trend eucritic material in these breccias.

2) Significant proportions of foreign materials are contained in these howardites. CM2 chondrites are present as individual clasts and, possibly, as fine-grained debris between individual mineral fragments and clasts. These CM2 materials may be derived from fine-grained material that resulted from impacts of carbonaceous chondrite meteorites on the HED parent body, or as accreted interplanetary dust (Zolensky *et al.*, 1996).

3) Also included are significant proportions of impact-modified materials, including monomict and polymict breccias, impact-melt breccias, and eucritic clasts with blackened pyroxenes.

4) Based on matrix mineral compositions, proportions of different types of clasts, bulk compositions, and calculated model compositions, it is possible to roughly approximate the proportions of the various types of materials that were mixed together to form these breccias. This approximation is, by weight, 30% diogenite, 25% main-group eucrite, 25% evolved eucrite, 17% cumulate eucrite, and 3% CM2 chondrite.

5) The calculated model composition of this mixture is similar to the bulk composition of EET 87513.

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