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Report

Survey and evaluation of eucrite bulk compositions

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Abstract–The purpose of this survey is to establish reference bulk elemental abundances for the eucrites and thereby provide the basis to test core formation models as well as partial melting, fractional crystallization and magma ocean theories for the eucrite parent body. In order to evaluate bulk elemental abundances for the eucrites, 296 peer-reviewed articles, monographs, theses or books and 143 abstracts dating from 1938 to 1997 were surveyed. Of the 101 eucrites having at least one set of elemental abundance analyses reported in the literature, 20 were selected for in-depth examination. The selection criteria of our sample were based on the total number of analyses available for a given eucrite and the total number of elements for which data exist. The mean bulk elemental abundance, 1σ standard deviation, and the percent deviation were calculated for each element in a given eucrite. In order to evaluate the quality of the mean abundances, the elements were then grouped according to availability of data and percent deviations. Possible reasons for the different deviations in the different groups are briefly discussed. From the major element abundances, the normative (CIPW) composition, the molar compositions of pyroxene, olivine and plagioclase, and the bulk densities were calculated and compared to petrographic observations. The calculated norms for the noncumulates agree well with the observations while the norms for the cumulates do not. Possible reasons for this are discussed. Unfortunately, analyses of many elements are poorly represented in the literature and many bulk analyses suffer from unacceptable levels of uncertainty. Therefore, future work requires bulk elemental analyses for some of the more poorly characterized elements in eucrites, especially those of key elements used for planetary modeling.

INTRODUCTION

The howardite-eucrite-diogenite (HED) achondrites were initially genetically linked in the mid-nineteenth century, petrogenically by Mason (1967) and *via* stable O isotopes by Clayton *et al.* (1976) and Clayton and Mayeda (1996). The eucrites are either basalts or basaltic cumulates (Duke and Silver, 1967). The diogenites are orthopyroxenites believed to be igneous cumulates (Mason, 1962), and the howardites are mechanical mixtures of clasts of both eucrites and diogenites (McCarthy *et al.*, 1972). These observations suggest that the HED achondrites formed on a single parent body, most probably an asteroid. It has been proposed that this asteroid is 4 Vesta (McCord *et al.*, 1970). This proposal is based upon several lines of evidence, the two principal ones being the similar reflection spectra of the eucrites and 4 Vesta (Binzel and Shui, 1993) and a family of Vestoids with semi-major axes between Vesta and the 3:1 or v_6 resonances (Knezevic *et al.*, 1991). (The Vestoids are small asteroids that have similar orbital parameters and spectral class to Vesta. The 3:1 or v_6 resonances are believed to be the trapdoors through which the HED meteorites enter Earth-crossing orbits.) The hypothesis of 4 Vesta being the source of the HED meteorites has been bolstered recently by new observations from the Hubble Space Telescope detailing the surface of 4 Vesta (Binzel *et al.*, 1997). This long fascination with the linkage between the HED meteorites themselves and their possible common origin on 4 Vesta has fostered the development of various models describing the formation and evolution of Vesta as the HED parent body.

However in order to evaluate and analyze these theories and models, we need a reliable bulk composition data set for all of the eucrites, cumulate and noncumulate, the howardites and the diogenites. A reliable bulk elemental abundance compilation serves many purposes. From bulk elemental data, element correlations can be derived that reveal element fractionations. These element fractionations place constraints on core formation, magma ocean and partial melting models. A large database allows verification of chemical trends for the entire meteorite clan unlike studies restricted to a limited number of meteorites. These trends themselves allow for improved characterization of meteorite groups and better classification of individual meteorites. This type of database enables researchers to evaluate the meteorite data *via* statistical techniques and becomes a guide for future analytical work on the particular meteorites and the particular elements that are found to be poorly characterized.

Unfortunately, there are no such recent, comprehensive, and widely disseminated compilations for the eucrites, howardites and diogenites. Therefore, as a partial solution, the purpose of this study is to survey the literature, compile all bulk elemental abundance data, provide an overview of the bulk and mineralogical compositions for the eucrites, and critically assess the analytical data in the literature.

SURVEY METHODOLOGY

After an extensive literature search, eucrite bulk element abundance data from 296 peer-reviewed articles, monographs, theses or books and 143 abstracts dating from 1938 to 1997 were collected in a spreadsheet and analyzed. The analysis included the computation of the mean, the 1σ standard deviation, the percent deviation and the total count of the number of data points for each element for each meteorite. All data were subjected to a 90% level confidence test. Those data points lying outside this confidence level or those listed as upper limits were not included in the grand averages. In a few literature sources, there were instances of internal inconsistencies between data tables and text and these data were also excluded (for example, typographical errors where an elemental abundance is listed both at ppb and ppm levels). No assumptions were made as to what the author "really meant." It is important to note that many authors, especially when making comparisons to new meteorites or new analytical techniques, repeat previously reported abundance determinations. Therefore, care was taken to avoid including duplicate data in the computations resulting in a final number of 887 individual eucrite bulk analyses of at least one element from the 439 sources.

Approximately 100 eucrites have more than one reference reporting a suite (*i.e.*, values for five or more elements) of bulk analytical data and those eucrites are listed in Table 1. Of these eucrites, only 38 have three or more analyses including more than five elements. Due to this dearth of data, only 20 eucrites were selected for detailed examination. The selection criteria were based on total number of analyses available for a given eucrite and the extent of these analyses, specifically the total number of elements for which data exist. Due to the inherent biases introduced by weathering effects in the Antarctic and other meteorite finds, falls were given preference. In order to save space, only the references actually cited herein or used to calculate the means of the selected eucrites appear in the reference section.

RESULTS

Meteorite Descriptions

The 20 eucrites selected for the in-depth analytical survey are described in Table 2. The table includes the mass, recovery location, and date of the fall or find. There are four unbrecciated meteorites (including one unbrecciated noncumulate), three cumulate eucrites (two falls and one find) and eleven monomict eucrites. Appendix 1 shows the specific references from which individual analyses were collected and incorporated into the database for each of the principal 20 meteorites. (Appendix 1 includes references to data listed as upper limits, although as previously stated, these numbers were not included in the grand means.) In an attempt to save space, these references are truncated and correspond to the full reference list with the bracketed notes serving as a guide to which elements were analyzed in each case. It is obvious from this list which meteorites have been studied extensively and which meteorites are not as well characterized. The petrographic descriptions in Table 2 are gleaned from the references listed in Appendix 1 and the following: Bogard *et al.* (1985), Carlson *et al.* (1988), Engelhardt (1963), Fredriksson and Kraut (1967), Graham *et al.* (1985), Harlow *et al.* (1979), Karpenko *et al.* (1991), Kraut and Phan (1980), Manhès *et al.* (1984), Marvin and Mason (1980, 1982), Metzler *et al.* (1994), Pun and Papike (1996), Reid and Score (1981), Takeda *et al.* (1983a,b), Wadhwa and Lugmair (1995), Warren and Jerde (1988) and Yamaguchi *et al.* (1994, 1996). If the nature of a particular meteorite is in question, then the appropriate references explaining the disagreement appear at the bottom of Table 2.

Bulk Elemental Abundances

The bulk elemental abundances from this survey are listed in Table 3 that is organized as follows. The element symbol and concentration unit are given in column one and two. The elements are listed in order of atomic number, except for the rare earth elements (REE), which have been separated out and are listed at the end for easy reference. Each meteorite name heads a set of four columns that contain in order: the calculated mean, the 1σ standard deviation, the percent deviation from the mean, and the total number of analyses used to calculate the mean. In the case where only two measurements exist for a particular element in a particular meteorite, the 1σ standard deviation and the percent deviation reflect the range of values. Obviously, where there is only one measurement, no uncertainties are given. The letter "N" in all tables signifies noncumulate eucrite while the letter "C" signifies cumulate eucrite.

Heterogeneity in bulk elemental analyses can be due to (1) the naturally low abundance of an element making the physical measurement difficult for the highly siderophile elements in eucrites (*i.e.*, Ni, Au and Pt), (2) analytical difficulties such as very short half-lived nuclides limiting the efficiency of neutron activation analyses or the requirement of chemical separation to decrease background radiation and increase gamma ray counting statistics, (3) weathering that is often a problem for finds such as the Antarctic meteorites, or (4) true elemental heterogeneity caused by mobility or volatility. Therefore, in order to better understand the role each of these play in bulk analyses of the eucrites, we separated the bulk elemental data into several groups based on number of analyses and percent deviation. This enabled us to see immediately which elements demonstrate heterogeneity and whether this could be due to a sampling problem. (For example, if there are only two reported abundances for a particular element that diverge greatly, then no statistical tests can be applied and the reason for the divergence cannot be determined.) Group one contains those elements for which the average number of analyses is >4 and with percent deviations of 15% or less

TABLE I. List of eucrites in database.*

A-881388	Cachari	Ibitira	Millbillillie	RKP92403	Y-791186
A-881394	Caldera	Jonzac	Moama	Serra de Magé	Y-791195
A-881467	Camel Donga	Juvinas	Moore County	Sioux County	Y-791438
ALH 76005	Chervony Kut	Kirbyville	Nagaria	Stannern	Y-791826
ALH 77302	Constantinople	Lakangaon	Nuevo Laredo	TIL82403	Y-792510
ALH 78040	EET 79011	LEW 85300	Padvarninkai	Y-74159	Y-792511
ALH 78132	EET 83232	LEW 85302	Palo Blanco Creek	Y-74356	Y-792769
ALH 80102	EET 87520	LEW 85303	Pasamonte	Y-74450	Y-793164
ALH 81001	EET 87542	LEW 86001	PCA82501	Y-75011	Y-793547
ALH 81006	EET 87548	LEW 86002	PCA82502	Y-75015	Y-793548
ALH 81007	EET 92025	LEW 87004	PCA91007	Y-78132	Y-793570
ALH 81009	EET 92027	LEW 87010	PCA91179	Y-790006	Y-794002
ALH 81010	EETA79004	LEW 87026	Peramiho	Y-790007	Y-794043
ALH 81011	EETA79005	LEW 87295	Piplia Kalan	Y-790020	Y-82037
Béréba	Emmaville	LEW 88005	PKP80224	Y-790122	Y-82049
Bouvante	Haraiya	Macibini	Pomozdino	Y-790260	Y-82066
Brient	HOW 88401	Medanitos	RKP80204	Y-790266	

*Only those eucrites having at least five elements included in the abundance analyses are listed here.

TABLE 2. General description of selected eucrites.

Meteorite	Recovered mass	Fall/ Find	Location	Date	Petrographic description
ALH 76005	1425.0 g	find	Antarctica	1976	brecciated, polymict, noncumulate
Béréba	16 kg	fall	Haute Volta	1924 June 27	brecciated, monomict, noncumulate
Bouvante	8.3 kg	find*	Bouvante-le Haut, France	1980 July 30	brecciated, dimict†, noncumulate
Cachari	23.5 kg	find	Azul, Argentina	1916 May	brecciated, monomict, noncumulate
Chervony Kut	~1.7 kg	fall	Sumy Region, Ukraine	1939 June 23	brecciated, monomict, noncumulate
EETA79004	390.3 g	find	Antarctica	1979	brecciated, monomict, noncumulate
EETA79005	450.9 g	find	Antarctica	1979	brecciated, polymict, noncumulate
Haraiya	1 kg	fall	Basti District, Uttar Pradesh, India	1878	brecciated, monomict, noncumulate
Ibitira	2.5 kg	fall	Martinho Campos, Brazil	1957 June 30	unbrecciated, monomict, noncumulate
Juvinas	91 kg	fall	Libonnès, France	1821 June 15	brecciated, monomict, noncumulate
Millbillillie	25.4 kg	find‡	Wiluna district, Western Australia	1960 October	brecciated, polymict§, noncumulate
Moore County	1.87 kg	fall	North Carolina, USA	1913 April 21	unbrecciated, cumulate
Nuevo Laredo	500 g	find	Tamoulipas, Mexico	1950	brecciated, monomict, noncumulate
Pasamonte	3–4 kg total	fall	Union County, New Mexico USA	1933 March 24	brecciated, polymict, noncumulate
Pomozdino	327 g	find*	Ustkulom, Komi Russia	1964	brecciated, monomict, noncumulate
Serra de Magé	+2 kg total	fall	Pesqueira, Pemambucao, Brazil	1923 October 1	unbrecciated, cumulate
Sioux County	4.1 kg total	fall	Nebraska, USA	1933 August 8	brecciated, monomict, noncumulate
Stannern	+52 kg total	fall	Iglau, Moravia, Czechoslovakia	1808 May 22	brecciated, monomict, noncumulate
Y-74450	235.6 g	find	Antarctica	1974	brecciated, polymict, noncumulate
Y-791195	100.29 g	find	Antarctica	1979	unbrecciated, cumulate

*Shortly after fall.
†Until work by Delaney *et al.* (1984a), this meteorite was described as monomict.
‡Fell 1960 October; recovered 1970.
§Metzler *et al.* (1995) described this meteorite as monomict.

and includes Na, Mg, Al, Si, Ca, Sc, Ti, Cr, Mn, Sr, Hf, Th, Eu, and Yb. If the cumulates (Moore County, Serra de Magé and Y-791195) are ignored, then Fe and La are also in this group. If the cumulates and Antarctic meteorites are ignored, Nd and Sm belong in this group as well. For La, the uncertainty seems to be tied to the number of analyses with more measurements decreasing the deviation from the mean. Given the number of analyses, the time period over which these have been made and the varying methods used, a percent deviation of 15% or less is considered homogeneous.

Group two consists of elements for which the average number of analyses is >4 but the percent deviation is >15%. This group consists of S, K, Co, Au, and U. In the literature, variations in abundance of S are most often attributed to weathering. However in the case of S, the variability cannot be attributed unambiguously to weathering as there are very few S data reported for the highly weathered Antarctic eucrites and the fall data vary greatly. Perhaps, this variability is caused by volatility. One reason for the observed data spread of the large ion lithophiles K and U may be indeed sample heterogeneities. Laul *et al.* (1986) have previously reported such data spreads for the shergottites, which are also basaltic achondrites. Laul *et al.* also remarked on the large heterogeneities for mobile elements such as Au.

Group three comprises those elements with the average number of analyses between one and three in a given eucrite and deviations of <15%. This group includes Li, Ga, Y, Zr, Ba, Pr, and Gd. Terbium and Dy are also in this group when cumulates and Antarctic meteorites are excluded. These trends suggest homogeneity but there are not enough values to show this statistically.

Group four are those elements with average number of analyses between one and three and with deviations >15%. This group comprises F, P, Ni, Cu, Zn, As, Se, Rb, Ag, Cd, In, Sb, Cs, Ta, Bi and Ce. Lodders (1998) has shown that the abundances of the elements Cu, Zn, Se, Ag, Cd, In, Ta, Bi are also highly variable in the shergottite-nakhlite-chassignite (SNC) meteorites. Therefore, these elements may very well be heterogeneous in basaltic achondrites that in turn could be due to the high volatility of most of these elements. Analytical difficulties can also cause the large deviations for elements such as Tl and Bi because of their low abundances. However, additional analyses of F, Ni, As, Rb, and Sb may provide information that will help determine whether the observed deviations of these elements are due to heterogeneities or other factors.

The difficulties associated with various analytical methods used in different laboratories are illustrated by the analyses of the Allende (CV2) chondrite. In 1969, the Allende chondrite meteorite fell. Because the meteorite was so large and fresh, four kilograms were carefully homogenized and distributed for analyses. Jarosewich *et al.* (1987) compiled and statistically analyzed all the data returned by various laboratories in order to check for homogeneity in the reference sample itself and for variance among different analytical techniques and laboratory groups. The variance analysis for 48 elements based on 75 replicate analyses showed only four elements that were not within the 95% confidence level of homogeneity

TABLE 3. Bulk elemental compositions for selected eucrites.*

		ALH 76005 (N)				Béréba (N)				Bouvante (N)				Cachari (N)				Chervony Kut (N)			
	unit	Bulk	1σ	%	#	Bulk	1σ	%	#	Bulk	1σ	%	#	Bulk	1σ	%	#	Bulk	1σ	%	#
Li	ppm	–				9	0.7	8	2	–				10			1	–			
Be	ppb	–				–				–				–				–			
B	ppb	–				–				–				–				–			
C	%	0.11	0.15	136	4	–				–				–				–			
F	ppm	–				53			1	–				–				–			
Na	ppm	3429	384	11	6	3298	247	7	8	3773	456	12	3	3778	234	6	4	3362	647	19	5
Mg	%	4.33	0.3	7	4	4.00	0.2	4	6	3.86	0.2	5	3	4.12	0.2	5	3	3.93	0.38	10	3
Al	%	6.47	0.1	1	4	6.85	0.2	3	6	5.56	0.6	12	3	7.03	0.4	6	3	6.65	0.18	3	3
Si	%	22.73	0.2	1	4	22.87	0.3	1	3	23.49	0.06	0.2	2	22.69	0.2	1	2	23.58	0.17	1	2
P	ppm	348	125	36	2	465	97	21	3	–				299	83	28	2	–			
S	%	0.16			1	0.21	0.03	13	6	–				0.03			2	–			
Cl	ppm	–				16			1	–				–				–			
K	ppm	472	63	13	5	330	62	19	7	565	82	15	3	388	42	11	3	352	130	37	3
Ca	%	6.64	0.5	7	7	7.43	0.2	2	6	7.47	0.2	2	6	7.22	0.1	2	3	7.47	0.4	5	3
Sc	ppm	31	3	8	3	30	1	4	5	31	1.2	4	5	34	6	17	3	29	4.1	14	4
Ti	ppm	4187	609	15	4	4838	982	20	6	6200	436	7	3	3735	47	1	3	4556	1102	24	2
V	ppm	68			1	73	9	12	4	51			1	115			1	98			1
Cr	ppm	2534	175	7	6	2172	169	8	6	2136	68	3	6	2589	504	19	4	2116	236	11	3
Mn	ppm	4213	152	4	5	4168	320	8	7	4092	98	2	3	5000	702	14	3	4185	417	10	2
Fe	%	14.46	0.7	5	6	14.77	0.4	3	7	15.27	0.4	3	7	14.91	0.1	0.5	3	14.03	0.68	5	5
Co	ppm	7	1	15	3	7	1.2	17	6	2	0.5	23	6	6	1.8	31	2	5	0.44	8	2
Ni	ppm	73	19	26	2	17			1	–				–				11			1
Cu	ppm	–				3	2	58	3	5	0.6	13	3	4			1	4			1
Zn	ppm	–				1.3	0.18	14	4	1.29			1	–				–			
Ga	ppm	–				1.5	0.11	7	4	1.80	0.344	19	3	–				–			
Ge	ppm	–				0.05			1	–				–				–			
As	ppm	–				0.12			1	0.034	0.007	19	3	–				–			
Se	ppm	–				0.318	0.13	42	3	0.19			1	–				–			
Br	ppm	0.27			1	0.067	0.05	70	2	–				–				–			
Rb	ppm	–				0.166	0.03	19	3	0.47			1	–				–			
Sr	ppm	86	17	20	3	75	6	8	4	98	9.9	10	2	83	2	3	3	66	0.71	1	2
Y	ppm	–				14	4	26	3	–				17	2.1	12	3	11			1
Zr	ppm	61			1	50	3	6	3	93	1.4	2	2	44	1.2	3	3	–			
Nb	ppm	–				3	1.1	33	2	–				4	1.6	40	2	–			
Mo	ppm	–				–				0.07			1	–				–			
Pd	ppb	–				–				–				–				–			
Ag	ppb	–				50	68	138	2	1.1			1	–				–			
Cd	ppb	–				5	6	131	2	0.95			1	–				–			
In	ppb	–				0.41	0.47	115	3	4			1	–				–			
Sn	ppb	–				–				–				–				–			
Sb	ppb	–				1.2			1	25	2	8	3	–				–			
Te	ppb	–				5			1	0.6			1	–				–			
I	ppb	–				–				–				–				–			
Cs	ppb	–				6.8	1	13	4	18.5			1	–				–			
Ba	ppm	34	1	3	3	32	5.8	18	4	59	4.2	7	2	50	2.6	5	2	38	2.83	7	2
Hf	ppm	1.49	0.05	3	3	1.25	0.18	14	4	2.8	0.1	3	6	1.08			1	1.49	0.11	7	2
Ta	ppb	194	9	5	2	145	7	5	2	420	13	3	5	140			1	220			1
W	ppb	580			1	63			1	178	37	21	3	–				–			
Re	ppb	–				–				–				–				–			
Os	ppb	–				0.02			1	0.005	0.004	80	2	–				–			
Ir	ppb	–				0.36	0.49	136	2	–				–				–			
Au	ppb	8.9			1	7	8	108	5	0.5	0.13	29	4	8			1	3			1
Hg	ppb	–				–				–				–				–			
Tl	ppb	–				0.31			1	0.72			1	–				–			
Pb	ppb	–				96			1	90			1	279			1	–			
Bi	ppb	–				4	5	127	2	0.38			1	–				–			
Th	ppb	369	10	3	3	315	42	13	7	620	60	10	5	–				580			1
U	ppb	130			1	95	2	3	4	175	26	15	3	–				–			
La	ppb	3530	413	12	3	2755	143	5	4	6240	278	4	6	2445	233	10	2	2925	742	25	2
Ce	ppb	9860	896	9	4	7700	1058	14	3	16350	636	4	2	6550	1344	21	2	9100			1
Pr	ppb	–				980			1	–				–				–			
Nd	ppb	5610	1396	25	4	5100	283	6	2	11237	1356	12	3	4310	184	4	2	–			
Sm	ppb	1965	384	20	6	1745	104	6	4	3648	291	8	6	1454	104	7	3	1820	240	13	2
Eu	ppb	667	24	4	4	613	5	1	4	843	34	4	5	615	21	3	2	580			1
Gd	ppb	2200			1	2300			1	5250	495	9	2	1872			1	–			
Tb	ppb	544	97	18	3	417	12	3	3	910	31	3	5	400			1	495	35	7	2
Dy	ppb	3630	1414	39	2	2480			1	5540	339	6	2	2485	304	12	2	2950			1
Ho	ppb	–				580			1	1330	85	6	2	–				770			1
Er	ppb	1730			1	1770			1	3500	283	8	2	1533			1	–			
Tm	ppb	–				–				515	21	4	2	–				–			
Yb	ppb	2257	45	2	3	1685	140	8	4	3258	108	3	5	1632	97	6	2	1795	389	22	2
Lu	ppb	291	21	7	4	260	8	3	4	470	18	4	6	247	18	7	2	300	14	5	2

*Bulk = abundance. 1σ = ± one standard deviation, except for n = 2, where the value reflects the range of values. % = percent deviation. # = number of analyses. N = noncumulate. C = cumulate.

TABLE 3. *Continued.*

	unit	EETA79004 (N) Bulk	1σ	%	#	EETA79005 (N) Bulk	1σ	%	#	Haraiya (N) Bulk	1σ	%	#	Ibitira (N) Bulk	1σ	%	#	Juvinas (N) Bulk	1σ	%	#
Li	ppm	–				–				–				–				7.8	3.7	48	2
Be	ppb	–				–				–				–				–			
B	ppb	–				–				–				–				965	474	49	2
C	%	–				–				0.468	0.03	6	6	–				–			
F	ppm	–				–				–				4			1	19			1
Na	ppm	2981	44	1	2	2994	5.3	0.2	2	3159	436	14	6	1352	223	16	4	3201	276	9	13
Mg	%	5.17			1	5.38			1	4.16	0.2	4	3	4.42	0.1	3	3	4.22	0.1	3	6
Al	%	5.95			1	6.20			1	6.52	0.2	3	5	6.56	0.4	6	3	6.93	0.2	2	9
Si	%	23.16			1	23.16			1	22.67	0.1	1	2	22.63	0.4	2	3	22.97	0.3	1	7
P	ppm	220			1	270			1	423			1	433	225	52	3	397	6.0	2	2
S	%	0.26			1	0.11			1	0.11	0.01	9	3	0.23	0.2	94	2	0.15	0.1	41	5
Cl	ppm	520			1	–				–				–				28.5	14.8	52	2
K	ppm	712	144	20	2	348	103	30	3	260	15	6	2	175	55	31	4	328	64	20	13
Ca	%	6.01	0.2	4	3	6.40	0.4	7	3	7.06	0.2	3	4	7.78	0.1	1	4	7.66	0.4	5	12
Sc	ppm	28	0.49	2	2	27	0.4	2	2	27	3	11	4	29	3.1	11	3	28	1.6	6	10
Ti	ppm	3837			1	3897			1	3289	151	5	3	5084	353	7	3	3713	231	6	6
V	ppm	–				–				94	20	21	2	–				85	16	19	2
Cr	ppm	2936	43	1	3	2818	12	0.4	3	2066	329	16	8	2187	346	16	5	1783	369	21	12
Mn	ppm	4090	155	4	2	3911	76	2	2	4349	278	6	5	3894	273	7	3	4037	197	5	9
Fe	%	14.06			1	13.47	0.2	2	3	14.77	0.7	5	7	13.94	1.3	9	5	13.90	0.9	6	12
Co	ppm	7	1.1	17	3	9	2.5	28	3	4	2.0	53	5	10	4.2	44	3	4.7	0.9	20	9
Ni	ppm	33			1	–				14	2.1	16	2	6			1	4	3.4	77	5
Cu	ppm	–				–				5			2	3.2	2.8	88	2	2.3	0.9	38	8
Zn	ppm	1.53			1	1.33			1	2.2	0.8	38	2	2.2	0.8	36	2	1.8	0.8	44	4
Ga	ppm	1.65	0.35	21	2	1.32	0.3	19	2	2.01	0.9	43	3	1.02			1	1.74	0.3	15	5
Ge	ppm	–				–				–				0.004			1	0.036	0.03	80	3
As	ppm	–				–				–				0.17	0.2	135	2	0.24	0.2	89	5
Se	ppm	0.66			1	–				0.27	0.2	58	2	0.08			1	0.14	0.1	63	2
Br	ppm	–				–				–				0.07			1	0.16	0.01	8	2
Rb	ppm	0.19			1	0.22			1	0.19	0.04	22	2	0.13			1	0.20	0.08	38	6
Sr	ppm	81	3.5	4	2	90	2.8	3	2	71	10	14	3	85.4			1	74.9	5.2	7	7
Y	ppm	–				–				14	0.6	4	3	–				16.5	0.7	4	5
Zr	ppm	41			1	–				37	1.7	5	3	–				44.9	1.6	4	3
Nb	ppm	–				–				2.1			1	–				2.7			3
Mo	ppm	–				–				–				0.045			1	0.015			1
Pd	ppb	–				–				–				–				0.4			1
Ag	ppb	4.8			1	9.0			1	13	8.2	63	2	14			1	58	48	82	4
Cd	ppb	52			1	23			1	6.5	0.3	4	2	29.8			1	20.3	16	79	3
In	ppb	1.49			1	8.97			1	0.24	0.04	18	2	–				1.45	0.1	7	4
Sn	ppb	–				–				–				–				–			
Sb	ppb	2.6			1	2.8			1	8.4	1.2	14	2	9.1	2.6	29	2	13.8	16	116	5
Te	ppb	3.9			1	6			1	1.1			1	0.5			1	9.4	1.3	14	2
I	ppb	–				–				–				–				40	6.4	16	2
Cs	ppb	11.2			1	9.1			1	9.0	3.2	35	2	8.3			1	6.3	1.4	22	4
Ba	ppm	31			2	30	0.7	2	2	32	7.6	24	3	–				30	2.8	9	4
Hf	ppm	1.28	0.08	6	2	1.32	0.07	5	2	1.02			1	1.1			1	1.3	0.1	10	6
Ta	ppb	170	28	17	2	175	7.1	4	2	–				–				148	19	13	3
W	ppb	–				–				–				99.5	57	58	2	30	7.0	23	5
Re	ppb	–				0.044	0.01	24	2	–				0.002			1	0.010			1
Os	ppb	–				0.565	0.11	19	2	–				–				0.008	0.006	75	5
Ir	ppb	–				–				–				0.004			1	0.096	0.08	83	4
Au	ppb	1.2	0.24	20	2	0.94			1	1.1	0.2	23	2	3.1	2	66	3	4.3	3.4	79	9
Hg	ppb	–				–				–				–				5010			1
Tl	ppb	18			1	26.3			1	2.9	2.4	82	2	0.41			1	0.67	0.5	71	3
Pb	ppb	–				–				–				–				–			
Bi	ppb	–				1.3			1	0.9	0.1	14	2	6.6			1	3.0	2.2	73	3
Th	ppb	300	28	9	2	325	21	7	2	–				–				297	67	23	6
U	ppb	92	20	22	3	114	5	4	3	129			1	88	14	15	3	123	51	41	7
La	ppb	2130	849	40	2	2625	1096	42	2	2465	50	2	2	2890			1	2582	238	9	12
Ce	ppb	7210	2249	31	2	8620	2234	26	2	6100			1	11000			1	6934	563	8	7
Pr	ppb	–				–				1200			1	–				967	23	2	3
Nd	ppb	2650			1	5550	2475	45	2	5000			1	–				4955	300	6	6
Sm	ppb	1380	707	51	2	1825	658	36	2	1790	156	9	2	2025	389	19	2	1623	128	8	12
Eu	ppb	547	61	11	2	554	37	7	2	520	85	16	2	685	21	3	2	624	36	6	10
Gd	ppb	1350			1	1200			1	1900			1	–				2292	278	12	6
Tb	ppb	320	99	31	2	425	106	25	2	350			1	500			1	402	53	13	6
Dy	ppb	1750			1	2000			1	2100			1	–				2863	275	10	6
Ho	ppb	460			1	540			1	900			1	–				533	98	18	3
Er	ppb	–				–				1700			1	–				1742	113	6	7
Tm	ppb	210			1	250			1	–				–				280			2
Yb	ppb	1505	262	17	2	1730	354	20	2	1590			1	1870	42	2	2	1602	188	12	14
Lu	ppb	225	35	16	2	250	42	17	2	310			1	395	35	9	2	255	24	9	12

*Bulk = abundance. 1σ = ± one standard deviation, except for n = 2, where the value reflects the range of values. % = percent deviation. # = number of analyses. N = noncumulate. C = Cumulate.

TABLE 3. *Continued.*

	unit	Millbillillie (N) Bulk	1σ	%	#	Moore County (C) Bulk	1σ	%	#	Nuevo Laredo (N) Bulk	1σ	%	#	Pasamonte (N) Bulk	1σ	%	#	Pomozdino (N) Bulk	1σ	%	#
Li	ppm	–				–				12.4			1	9	2.2	24	4	–			
Be	ppb	–				–				–				39	1.5	4	3	–			
B	ppb	1100			1	–				430			1	3340	3196	96	2	–			
C	%	–				–				–				0.07	0.01	14	7	–			
F	ppm	–				60			1	51			1	42	10.8	26	3	–			
Na	ppm	3149	373	12	4	3130	140	4	4	3880	287	7	6	3668	595	16	10	3314	323	10	3
Mg	%	3.86	0.56	14	4	5.45	0.33	6	3	3.33	0.06	2	3	3.92	0.15	4	7	5.53	0.41	7	3
Al	%	6.82	0.16	2	4	7.77	0.7	9	5	6.37	0.14	2	5	6.59	0.3	5	7	5.86	0.29	5	3
Si	%	24.10	0.03	0.1	2	22.55	0.05	0.2	2	23.14	0.05	0.2	3	22.94	0.54	2	7	22.99	0.49	2	3
P	ppm	340			1	157			1	480			1	429	67	16	4	1135			1
S	%	0.05	0.06	120	2	0.33	0.03	8	4	–				0.08	0.03	43	10	1.02			1
Cl	ppm	–				5.65	0.21	4	2	–				16	9.1	56	3	–			
K	ppm	462	215	47	3	191	31.6	17	7	417	40	10	8	358	58	16	15	350	87.2	25	3
Ca	%	7.28	0.2	3	2	7.35	0.51	7	4	7.36	0.07	1	4	7.33	0.15	2	11	7.07	0.56	8	3
Sc	ppm	30.9	1.6	5	2	22.5	2.12	9	2	38.6	4.5	12	6	31.5	6.0	19	7	27.3	3.7	14	3
Ti	ppm	4344	484	11	4	2194	379	17	3	5198	433	8	3	4330	300	7	5	5392	966	18	3
V	ppm	75	11	15	2	92	31	34	2	61	4	7	2	70	18	25	3	72			2
Cr	ppm	2424	437	18	4	2650	624	24	3	1911	73	4	4	2000	289	14	9	3506	488	14	3
Mn	ppm	4559	340	7	4	3526	468	13	3	4437	98	2	4	4113	237	6	9	4118	145	4	3
Fe	%	14.67	0.56	4	3	11.52	2.1	18	5	15.06	0.61	4	4	14.43	0.57	4	9	13.72	2.5	18	3
Co	ppm	8.3	2.4	29	2	5.0	1.7	33	4	2.1	0.1	4	3	5.0	1.5	30	5	9.4	3.5	38	4
Ni	ppm	150			1	12	7.7	66	4	3			1	12	11	92	4	2.1	1.4	66	2
Cu	ppm	–				5.5	2.12	39	2	7			1	2.45	2.19	89	2	–			
Zn	ppm	1.3			2	1.1	0.2	19	3	–				2.0	0.29	14	4	20.5	10.6	52	2
Ga	ppm	1.8			1	1.8	0.25	14	2	1.3	0.42	33	2	1.65	0.19	12	5	1.62	0.69	42	2
Ge	ppm	–				0.007			1	–				0.035	0.01	20	2	0.252	0.17	66	2
As	ppm	–				–				–				0.067	0.08	114	2	0.0856			1
Se	ppm	–				0.35	0.15	42	3	0.002			1	0.05	0.04	72	3	–			
Br	ppm	–				0.05	0.03	64	3	–				0.149			1	–			
Rb	ppm	–				0.06	0.02	43	4	0.37	0.02	6	6	0.24	0.05	21	11	–			
Sr	ppm	88			1	71	5.5	8	6	82.8	9.1	11	5	76.7	4.5	6	12	112.5	6.4	6	2
Y	ppm	–				9			1	–				17			1	–			
Zr	ppm	50			1	22			1	71			1	57	4.4	8	6	84	74	88	2
Nb	ppm	–				–				–				3.6	0.07	2	2	–			
Mo	ppm	–				–				–				0.027			1	–			
Pd	ppb	8.5	0.7	8	2	0.4			1	–				–				–			
Ag	ppb	–				2.6	0.77	30	3	–				0.49	0.33	66	2	–			
Cd	ppb	4.7	3.1	65	3	12.2	7.14	59	2	–				28.2	26.7	95	2	–			
In	ppb	–				0.09	0.05	58	2	–				3.23	0.37	11	4	–			
Sn	ppb	395	35	9	2	–				–				–				–			
Sb	ppb	–				3.3	2.4	71	3	–				3.2	2.5	80	2	65			1
Te	ppb	6	2.8	47	2	3	1.3	45	3	–				5.1	4.4	86	2	–			
I	ppb	–				135	21	16	2	–				108	44	41	4	–			
Cs	ppb	–				0.8	0.13	16	2	16.9	3.69	22	3	10.9	2.0	19	5	–			
Ba	ppm	29	1.0	3	3	26	7	27	2	42	8	18	6	32.5	3.2	10	6	59.5	3.5	6	2
Hf	ppm	2.59	1.9	72	2	0.61			1	1.61	0.01	0.4	2	1.24	0.16	13	3	2.21	0.35	16	2
Ta	ppb	170			1	–				181	3.5	2	2	169	48	28	3	257	51	20	3
W	ppb	240			1	–				–				38			1	380			1
Re	ppb	0.004	0.003	67	2	0.041	0.04	110	3	0.019	0.02	89	2	–				0.003			1
Os	ppb	0.004	0.002	62	2	0.003			1	0.219	0.20	90	2	–				0.009			1
Ir	ppb	–				–				0.083			1	0.62	0.04	7	2	0.035	0.04	107	2
Au	ppb	–				0.3	0.3	87	3	1.5			1	0.30	0.23	76	5	0.63	0.36	58	2
Hg	ppb	–				2740			1	78			1	–				–			
Tl	ppb	–				0.08	0.01	9	2	–				0.29			1	–			
Pb	ppb	–				25			1	265	102	39	3	289			1	–			
Bi	ppb	–				0.5	0.13	28	2	–				1.1	0.06	5	3	–			
Th	ppb	350			1	62			1	466	22	5	8	355	52	15	3	695	21	3	2
U	ppb	90			1	27	15	57	9	133	15	11	12	92	22	24	7	190	14	7	2
La	ppb	2985	304	10	2	1160	147	13	3	3923	112	3	4	3106	222	7	8	5600	566	10	2
Ce	ppb	5310	2857	54	2	3000			1	10433	497	5	6	8043	474	6	7	13900	990	7	2
Pr	ppb	–				430			1	1470			2	1273	23	2	3	1200			1
Nd	ppb	3985	1902	48	2	2120			1	7567	771	10	6	5413	586	11	9	9950	1202	12	2
Sm	ppb	1350	538	40	2	886	12	1.4	3	2258	73	3	4	1844	133	7	9	3050	354	12	2
Eu	ppb	623	32	5	3	570	14	2	2	740	21	3	8	663	35	5	9	845	92	11	2
Gd	ppb	1770	608	34	2	–				2453	61	2	4	2700	107	4	5	2700			1
Tb	ppb	390			1	–				565	29	5	4	477	40	8	3	780			2
Dy	ppb	2390	594	25	2	–				3985	476	12	4	3232	219	7	5	5000			1
Ho	ppb	560			1	–				840			2	710	35	5	3	1030			1
Er	ppb	1310	42	3	2	–				2858	304	11	4	1853	276	15	7	1600			1
Tm	ppb	320			1	–				480			2	300			2	450			2
Yb	ppb	1527	107	7	3	1000	42	4	2	2363	156	7	6	1785	161	9	8	2720	170	6	2
Lu	ppb	246	16	7	5	200	42	21	2	323	26	8	4	370	121	33	8	405	21	5	2

*Bulk = abundance. 1σ = ± one standard deviation, except for n = 2, where the value reflects the range of values. % = percent deviation. # = number of analyses. N = noncumulate. C = cumulate.

TABLE 3. *Continued.*

	unit	Serra de Magé (C)				Sioux County (N)				Stannern (N)				Y74450 (N)				Y791195 (C)			
		Bulk	1σ	%	#	Bulk	1σ	%	#	Bulk	1σ	%	#	Bulk	1σ	%	#	Bulk	1σ	%	#
Li	ppm	2.7			1	8.4	0.59	7	2	10	3.8	38	2	10			1	–			
Be	ppb	126			1	274	2	1	3	–				709			1	–			
B	ppb	–				–				3390	3691	109	2	–				–			
C	%	0.05			1	0.06	0.01	14	7	–				–				–			
F	ppm	–				43	30	71	2	48	39.7	83	2	–				–			
Na	ppm	2427	512	21	6	3040	349	11	11	4031	459	11	11	3428	630	18	3	2876	117	4	6
Mg	%	5.88	0.97	16	6	4.41	0.36	8	7	4.23	0.24	6	5	4.54	0.3	7	3	4.61	0.1	2	5
Al	%	8.91	1.44	16	7	7.08	0.56	8	8	6.47	0.37	6	8	6.03	0.3	5	3	7.08	0.2	3	5
Si	%	22.33	0.62	3	6	23.10	0.17	1	7	23.00	0.45	2	5	22.61	0.4	2	3	23.15	0.4	2	5
P	ppm	201	60	30	3	392	1.4	0.4	4	556	105	19	3	436			1	174	62	36	2
S	%	0.13	0.09	69	3	0.14	0.05	38	5	0.19	0.12	65	7	0.18	0.1	41	2	0.25	0.3	118	2
Cl	ppm	16			1	12			1	34.5			1	–				–			
K	ppm	71	19.5	28	4	302	34	11	14	646	78	12	15	453	36	8	4	320	56	18	6
Ca	%	7.90	1.0	13	7	7.34	0.15	2	11	7.54	0.31	4	11	6.95	0.1	2	5	7.38	0.1	2	6
Sc	ppm	18.3	4.28	23	6	28.6	2.1	7	8	31.2	0.85	3	8	30.0			1	29.7	1.0	3	2
Ti	ppm	875	191	22	5	3468	218	6	8	5860	272	5	6	5558	613	11	3	1141	450	39	5
V	ppm	116	46	40	3	102	17	17	2	77	12	16	2	69	2.5	4	2	72			1
Cr	ppm	2771	881	32	8	2165	222	10	13	2081	330	16	10	2689	421	16	3	2233	122	5	5
Mn	ppm	3229	654	20	6	4287	304	7	11	3921	361	9	9	4153	228	5	3	4284	168	4	4
Fe	%	9.60	1.8	19	9	14.10	1.4	10	14	14.10	1.04	7	11	14.18	0.2	2	4	13.62	0.2	1	5
Co	ppm	7.4	1.98	27	6	5.6	1.5	27	9	6.6	3.4	52	9	12			1	6.1	0.1	2	2
Ni	ppm	7	8.49	121	2	16	3.5	23	2	7	2.8	40	2	24			1	12.1	10	83	3
Cu	ppm	2.66	0.48	18	2	3.37	3.45	102	6	9.5	9.0	95	6	2.22			1	–			
Zn	ppm	0.67	0.09	14	3	1.31	0.5	38	4	3.64	3.56	98	3	1.44			1	0.92			1
Ga	ppm	1.44	0.02	1	2	1.39	0.18	13	3	1.63	0.3	19	6	1.46			1	–			
Ge	ppm	0.003			1	0.033			1	0.08			1	–				–			
As	ppm	0.15			1	0.003	0.001	47	2	0.02	0.02	93	2	0.006			1	–			
Se	ppm	0.31	0.26	83	4	0.25			1	0.35	0.08	24	2	0.37			1	–			
Br	ppm	0.03	0.02	71	2	0.11			1	0.06			1	0.047			1	0.08			1
Rb	ppm	0.05	0.02	32	3	0.21	0.05	22	6	0.72	0.15	20	4	0.41	0.1	24	2	–			
Sr	ppm	56.9	7.3	13	3	71.7	3.8	5	6	88.8	6	7	7	79.1	5.7	7	3	83.0	24	29	2
Y	ppm	19			1	13	1.4	11	4	27	1.2	4	3	–				–			
Zr	ppm	14			1	44	3.9	9	5	88	1.1	1	3	66	2.9	4	2	–			
Nb	ppm	–				2.7	0.15	6	3	5.5	1.13	21	2	–				–			
Mo	ppm	–				–				0.039	0.01	18	2	–				–			
Pd	ppb	–				–				–				–				–			
Ag	ppb	1.9	1.2	66	3	3.6	2.7	73	2	56.0	22.6	40	2	–				–			
Cd	ppb	5.57	4.31	77	3	6.9			1	16.4	20.7	126	3	–				–			
In	ppb	0.38	0.5	133	2	0.283	0.2	75	3	0.50	0.46	92	4	–				–			
Sn	ppb	–				–				–				–				–			
Sb	ppb	0.54	0.2	42	2	3.47	0.9	27	3	15.5	17.7	114	2	–				17			1
Te	ppb	1.5	0.6	44	2	–				7.0			1	–				–			
I	ppb	–				19.3	9.2	48	3	830	240	29	2	–				–			
Cs	ppb	1.4	0.6	44	3	9.9	1.7	17	4	15.6	1.25	8	3	19			1	–			
Ba	ppm	10.2	3.4	33	3	29.7	3.7	12	3	50.1	3.2	6	5	43.4	2.9	7	3	–			
Hf	ppm	0.13	0.02	16	2	1.10	0.11	10	3	2.36	0.55	23	7	1.95	0.1	7	3	0.41	0.2	58	2
Ta	ppb	80			1	132	35.1	27	3	405	88	22	4	300			1	20			1
W	ppb	–				44	9.9	22	2	126	36	29	2	85			1	–			
Re	ppb	0.001			1	–				–				0.7			1	0.002			1
Os	ppb	–				–				–				–				0.008			1
Ir	ppb	0.084	0.1	138	2	–				0.12	0.01	8	3	–				0.005			1
Au	ppb	1.28	1.3	102	4	0.27	0.1	43	4	6.85	9.43	138	6	0.27			1	–			1
Hg	ppb	210			1	–				9120			1	–				–			
Tl	ppb	0.075	0.06	85	2	0.2			1	2.14	2.21	103	2	–				–			
Pb	ppb	24			1	193			1	119			1	–				–			
Bi	ppb	1.1	1.2	104	3	0.3	0.17	68	2	4.5	2.67	59	2	–				–			
Th	ppb	53			1	245	54	22	4	610	96	16	7	–				110			1
U	ppb	13	4	32	4	103	29	28	4	187	23.9	13	8	136			1	–			
La	ppb	387	170	44	3	2340	569	24	8	5166	320	6	11	4190	849	20	2	495	7.1	1	2
Ce	ppb	730			1	5450	1909	35	2	13344	694	5	8	11625	530	5	2	1830	42	2	2
Pr	ppb	–				–				1980	28	1	2	1900			1	–			
Nd	ppb	–				–				10337	885	9	6	8115	969	12	2	1180			1
Sm	ppb	232	110	48	4	1280	136	11	5	3227	175	5	10	2590	269	10	2	379	40	11	2
Eu	ppb	411	83	20	4	562	68	12	6	808	47	6	12	704	6	1	2	445	7.1	2	2
Gd	ppb	–				–				4357	223	5	3	3330	99	3	2	–			
Tb	ppb	42	26	62	3	368	90	24	4	748	42	6	6	660			1	120	28	24	2
Dy	ppb	600			1	2600			1	4910	160	3	5	4010	269	7	2	–			
Ho	ppb	–				–				1090	35	3	3	970			1	–			
Er	ppb	–				–				3073	142	5	6	2560	269	10	2	–			
Tm	ppb	–				–				467	6	1	3	–				–			
Yb	ppb	235	135	57	3	1448	288	20	6	2663	314	12	12	2455	219	9	2	550	42	8	2
Lu	ppb	49	17	35	4	235	35	15	6	408	28	7	9	348	10	3	3	87	5	6	2

*Bulk = abundance. 1σ = ± one standard deviation, except for n = 2, where the value reflects the range of values. % = percent deviation. # = number of analyses. N = noncumulate. C = cumulate.

under these stringent conditions. These were O, Cs, Ce and Tb. They suggested that the deviations for these elements resulted from undetermined analytical problems. Despite this, Tb has a low deviation in our survey, but analytical uncertainties may help to explain the variations in abundances for Cs and Ce. In three separate studies which included Ce, Shimizu *et al.* (1983a,b) and Mittlefehldt and Lindstrom (1991) showed that anomalies in this element exist in the Antarctic meteorites regardless of type, which suggests that weathering may also contribute to the deviation of Ce. No data were found for O abundance in these eucrites.

The last group of elements in our survey consists of Be, B, C, Cl, V, Ge, Br, Nb, Pd, Sn, Te, I, W, Re, Os, Ir, Hg, Tl, Pb, Ho, Er and Tm. So few analyses of these elements have been reported that no deviations can be computed and no evaluation made regarding sample heterogeneity. This is regrettable as Ge, Nb, W, Re, Os, and Ir are often used as key elements in planetary differentiation modeling.

In examining these data in general, we are reminded of which elements are difficult to analyze (or analyze accurately) and which are not typically determined by routine methods such as neutron activation analyses. For example, no analytical data could be found for the elements Ru, Rh, and Pt in the selected eucrites. Unfortunately, the most obvious characteristic of Table 3 is the white space. Considering that the eucrites in Table 3 are the most analyzed of all the eucrites, the paucity of data is unsatisfactory. Therefore, Table 3 should function as a guide for future work and serve to remind us of the importance of basic research.

Mineralogical Composition

Table 4 is a list of the major element oxides calculated from the mean elemental abundance values for the selected eucrites from Table 3. From the data in Table 4, the normative (CIPW) composition in wt% and vol%, the molar compositions of pyroxene, olivine and plagioclase, and the bulk densities were calculated and appear in Table 5. The bulk densities of the eucrites in Table 5 were calculated from the mineral densities (Robie and Hemingway, 1995) of the minerals in the CIPW norm. The densities for the three cumulate eucrites Moore County, Serra de Magé and Y-791195 are uniformly lower (average of 3.15 g/cm^3) than the densities of the noncumulates (3.21 g/cm^3) because of the increase in the amount of plagioclase present and to the substitution of Mg for Fe in the cumulates. Serra de Magé is the only eucrite of the 20 selected with any normative olivine. This is in accordance with the petrologic observations of Prinz *et al.* (1980) and Delaney *et al.* (1984b,c).

In examining Tables 4 and 5, we see that the totals are <100% for ALH 76005, EETA79004, EETA79005 and Y-74450 and are >100% for Millbillillie. In the CIPW, all the Fe is taken as FeO and does not account for weathering of FeO to Fe_2O_3 in the Antarctic meteorites. When an estimated amount of Fe_2O_3 is included, the CIPW totals approach 100. According to the Antarctic meteorite database, EETA79004 and EETA79005 are suspected to be pairs but show different degrees of visible weathering. Meteorite EETA79004 is classified as an "A" and EETA79005 is classified as a "B" where A = minor rustiness and B = moderate rustiness. However, if the CIPW norm can be taken as a guide, both EETA79004 and EETA79005 seem to be moderately affected.

As for Millbillillie, we found only two reported Si values in the literature and they seem anomalously high. If the average Si value taken from the noncumulates in Table 4 is substituted into the normative calculation, the totals reduce to 100%. Again, this underlines the need for more analytical studies to be performed on the eucrites.

In comparing the calculated norm with actual petrographic modal analyses, we find excellent agreement for the noncumulate meteorites. In comparing total pyroxene and plagioclase abundances, there is a deviation of <5% between the normative calculations and the petrographic observations of Delaney *et al.* (1984c) for the meteorites ALH 76005, Béréba, Bouvante, Cachari, Chervony Kut, EETA79004, EETA79005, Haraiya, Juvinas, Millbillillie, Nuevo Laredo, Pasamonte, Sioux County, Stannern, and Y-74450. Wilkening and Anders (1975) and Steele and Smith (1976) both examined

TABLE 4. Average major element composition (wt%) of selected eucrites.

Meteorite	Type*	SiO_2	Al_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	Cr_2O_3	MnO	FeO	P_2O_5	S	Sum
ALH 76005	N	48.6	12.2	7.2	9.3	0.46	0.06	0.70	0.37	0.54	18.8	0.08	0.16	98.5
Béréba	N	48.9	12.9	6.6	10.4	0.44	0.04	0.81	0.32	0.54	19.0	0.11	0.21	100.3
Bouvante	N	50.3	10.5	6.4	10.4	0.51	0.07	1.03	0.31	0.53	19.7			99.7
Cachari	N	48.5	13.3	6.8	10.1	0.51	0.05	0.62	0.38	0.65	19.2	0.07	0.03	100.2
Chervony Kut	N	50.4	12.6	6.5	10.5	0.45	0.04	0.76	0.31	0.54	18.0			100.1
EETA79004	N	49.5	11.3	8.6	8.4	0.40	0.09	0.64	0.43	0.53	18.1	0.05	0.26	98.3
EETA79005	N	49.5	11.7	8.9	9.0	0.40	0.04	0.65	0.41	0.51	17.3	0.06	0.11	98.5
Haraiya	N	48.5	12.3	6.9	9.9	0.43	0.03	0.55	0.30	0.56	19.1	0.10	0.11	98.6
Ibitira	N	48.4	12.4	7.3	10.9	0.18	0.02	0.85	0.32	0.50	17.9	0.10	0.23	99.1
Juvinas	N	49.1	13.1	7.0	10.7	0.43	0.04	0.62	0.26	0.52	17.9	0.09	0.15	99.9
Millbillillie	N	51.3	12.9	6.4	10.2	0.42	0.06	0.78	0.35	0.59	18.9	0.08	0.05	102.1
Moore County	C	48.2	14.7	9.0	10.3	0.42	0.02	0.37	0.39	0.46	14.8	0.04	0.33	99.0
Nuevo Laredo	N	49.5	12.0	5.5	10.3	0.52	0.05	0.87	0.28	0.57	19.4	0.11		99.1
Pasamonte	N	49.1	12.5	6.5	10.3	0.49	0.04	0.72	0.29	0.53	18.6	0.10	0.08	99.1
Pomozdino	N	49.2	11.0	9.2	9.9	0.45	0.04	0.90	0.51	0.53	17.6	0.26	1.02	100.6
Serra de Magé	C	47.8	16.8	9.8	11.1	0.33	0.01	0.15	0.41	0.42	12.3	0.05	0.13	99.2
Sioux County	N	49.4	13.4	7.3	10.3	0.41	0.04	0.58	0.32	0.55	18.1	0.09	0.14	100.6
Stannern	N	49.2	12.2	7.0	10.6	0.54	0.08	0.98	0.30	0.51	18.1	0.13	0.19	99.8
Y-74450	N	48.4	11.4	7.5	9.7	0.46	0.05	0.93	0.39	0.54	18.3	0.10	0.18	98.0
Y-791195	C	49.5	13.4	7.6	10.3	0.39	0.04	0.19	0.33	0.55	17.5	0.04	0.25	100.1

*N stands for noncumulate and C stands for cumulate.

TABLE 5. Calculated normative mineralogy (CIPW) and density of selected eucrites.*

		ALH76005 (N)	Béréba (N)	Bouvante (N)	Cachari (N)	Chervony Kut (N)	EETA79004 (N)	EETA79005 (N)	Haraiya (N)	Ibitira (N)	Juvinas (N)
wt%											
px		57.6	58.2	61.7	58.7	57	59.5	59.4	59.2	59	57.9
ol		0	0	0	0	0	0	0	0	0	0
plag		35.4	37.1	30.9	38.4	36.3	32.7	33.6	35.4	34.6	37.6
il		1.3	1.5	2.0	1.2	1.4	1.2	1.2	1.0	1.6	1.2
chr		0.6	0.5	0.5	0.5	0.5	0.6	0.6	0.4	0.5	0.4
ap		0.2	0.2	0	0.2	0	0.1	0.1	0.2	0.2	0.2
qz		3.1	2.6	4.7	1.2	4.9	3.9	3.5	2.4	3.0	2.5
Sum		98.2	100.1	99.8	100.2	100.1	98	98.4	98.6	98.9	99.8
vol%											
px		52.6	52.1	56.3	52.4	50.9	54.8	54.6	53.9	54	52.1
ol		0	0	0	0	0	0	0	0	0	0
plag		42.1	43.2	36.4	44.9	41.9	39	39.8	41.9	40.6	43.6
il		0.9	1.0	1.3	0.8	1	0.8	0.8	0.7	1.1	0.8
chr		0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.3	0.3	0.2
ap		0.2	0.2	0	0.1	0	0.1	0.1	0.2	0.2	0.2
qz		3.8	3.1	5.7	1.4	5.9	4.8	4.2	2.9	3.7	3.1
Sum		100	99.9	100	100	100	99.9	99.9	99.9	99.9	100
Mineral composition (mol%)											
px	en	37	34	31	34	34	42	43	34	36	36
	fs	51	52	50	52	50	48	45	52	48	49
	ws	11	13	18	12	15	9	10	12	15	14
	rh†	1	1	1	2	1	1	2	2	1	1
plag	an	87	89	84	87	88	88	89	89	95	89
	ab	12	10	15	12	11	11	10	10	5	10
	or	1	1	1	1	1	1	1	1	0	1
Whole rock densities											
g/cm^3		3.22	3.21	3.22	3.21	3.18	3.22	3.21	3.22	3.21	3.19

*N = noncumulate; C = cumulate. †Rhodonite $MnSiO_3$.

TABLE 5. *Continued.*

		Millbillillie (N)	Moore County (C)	Nuevo Laredo (N)	Pasamonte (N)	Pomozdino (N)	Serra de Magé (C)	Sioux County (N)	Stannern (N)	Y-74450 (N)	Y-791195 (C)
wt%											
px		57.2	54.8	57.1	57.7	62.5	49.9	57.9	58.6	59.2	58.2
ol		0	0	0	0	0	1.5	0	0	0	0
plag		37.1	41.8	35	36.2	31.9	47.2	38.3	35.7	33.1	38.2
il		1.5	0.7	1.7	1.4	1.7	0.3	1.1	1.9	1.8	0.4
chr		0.5	0.6	0.4	0.4	0.8	0.6	0.5	0.4	0.6	0.5
ap		0.2	0.1	0.3	0.2	0.6	0.1	0.2	0.3	0.2	0.1
qz		5.8	0.7	4.7	3.3	2.1	0	2.5	2.8	2.9	2.4
Sum		102.3	98.7	99.2	99.2	99.6	99.6	100.5	99.7	97.8	99.8
vol%											
px		49.7	49.7	51.5	52.2	56.7	44.5	51.5	53.1	54.9	52.2
ol		0	0	0	0	0	1.3‡	0	0	0	0
plag		42	48.5	41.1	42.4	37.6	53.6	44.2	41.7	39.6	44.3
il		1.0	0.5	1.1	0.9	1.2	0.2	0.7	1.2	1.2	0.2
chr		0.3	0.4	0.3	0.3	0.5	0.4	0.3	0.3	0.4	0.3
ap		0.2	0.1	0.2	0.2	0.5	0.1	0.2	0.3	0.2	0.1
qz		6.8	0.8	5.8	4	2.6	0	3.0	3.4	3.7	2.9
Sum		100	100	100	100	99.1	100.1	99.9	100	100	100
Mineral composition (mol%)											
px	en	33	47	29	33	43	53	37	35	37	38
	fs	52	42	54	51	43	37	50	48	48	48
	ws	13	10	15	14	13	9	12	15	13	12
	rh†	2	1	1	2	1	1	1	2	2	2
plag	an	89	91	86	87	87	94	90	85	87	90
	ab	10	9	13	12	12	6	9	14	12	9
	or	1	0	1	1	1	0	1	1	1	1
Whole rock densities											
g/cm^3		3.19	3.16	3.20	3.20	3.25	3.11	3.19	3.20	3.22	3.19

*N = noncumulate; C = cumulate. †Rhodonite $MnSiO_3$. ‡Fa_{41} and Fo_{59}.

the same thin sections of Ibitira and estimated the bulk pyroxene to be 60 vol% and the bulk plagioclase to be 30 vol%. The deviation between these estimates and the normative calculations is ~16%. However *via* microprobe analyses, Steele and Smith (1976) determined the mineral compositions of selected pyroxene and plagioclase grains to be $En_{37}Fs_{48}Wo_{15}$ and An_{94}, respectively, which match almost precisely the percentages derived from our normative calculation. Thus, the section analyzed for modal composition may not be representative of the whole rock. Warren *et al.* (1990) observed that Pomozdino exhibits two distinct types of pyroxenes with Wo_9 and $Wo_{>30}$. Despite this, their average pyroxene and plagioclase composition (based on seven clasts and three matrix samples) deviates by <4% from the normative calculations.

However, the agreement between modal and normative composition shown by the noncumulate eucrites does not hold for the cumulate eucrites Moore County, Serra de Magé and Y-791195. The percent deviation between the calculated normative mineralogies and the modal mineralogies reported by Delaney *et al.* (1984b,c) for Y-791195 is >10% and is on the order of 20 to 30% for Moore County and Serra de Magé. (Note that the average area of the thin sections examined by Delaney *et al.* for these cumulate eucrites is 240 mm^2.) This discrepancy can be due to sample heterogeneity or errors in the petrologic and/or in the analytical studies. However, it seems too great a coincidence that the discrepancies arise only for the cumulate eucrites. By going back to Table 3, we can calculate the percent deviation in the Fe and Mg abundances of the cumulate eucrites *vs.* the noncumulate eucrites. The average percent deviation of Fe for Moore County and Serra de Magé is 18.5% while the average for the noncumulates is 5.9%. The percent deviation of Mg for Moore County and Serra de Magé is 11.5% *vs.* the 6.7% of the noncumulates. Heterogeneity in these two elements could easily account for the observed discrepancies between the modal and the normative mineralogies, especially given that bulk analyses used to calculate the normative mineralogies are determined on samples ranging in mass of 300 μg to 2 g and most modal mineralogies are done on thin section areas of ~100 to 400 mm^2. This seems to indicate that heterogeneities exist on at least the centimeter scale in these cumulate eucrites. Therefore, normative mineralogies for the cumulates should be viewed with the requisite caution, and petrographic observations on large sections of the cumulate eucrites are needed to determine the scale of the heterogeneities.

Bearing in mind any possible heterogeneities, we also see that the calculated enstatite percentages are higher in the cumulates than the noncumulates and that the calculated wollastonite percentages are lower in the cumulates than the noncumulates. The one exception is Pomozdino, which is classified as noncumulate. Pomozdino is an anomalous, high Mg yet REE-rich eucrite (Warren *et al.*, 1990). Petrographically and normatively, Pomozdino has a slightly higher average percentage of enstatite and a slightly lower average percentage of wollastonite than the other noncumulate eucrites. Furthermore, we observe that the percent deviation of the Fe bulk abundance for Pomozdino is 15% in line with the cumulate eucrites. Therefore, we concur with Hsu and Crozaz (1997), Warren and Jerde (1988) and Warren (1997) that Pomozdino most probably has some type of cumulate component incorporated into it.

SUMMARY

The purpose of this study is to establish reference bulk elemental abundances for the eucrites and, thereby, provide the basis to test core formation models as well as partial melting, fractional crystallization and magma ocean theories. In order for a particular model or theory to be accepted, it must reproduce the abundances presently observed in eucrites. Specifically, monomict eucrites are used in planetary modeling, while the polymict bulk data can be useful in calculating the proportions of various lithic components in polymict eucrites. However, in spite of compiling and evaluating 887 individual analyses, we have shown that more analytical data are needed as many of the elements most important for judging the merit of competing evolutionary theories are poorly represented and/or suffer from unacceptable levels of uncertainties. Therefore, future work requires bulk abundance analyses of some of the more poorly characterized elements in several eucrites. Such new data, along with the current data set, can provide an improved reference composition for use in modeling the evolution of the eucrite parent body.

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