

GEOCHEMISTRY AND PETROLOGY OF A SUITE OF TEN YAMATO HED METEORITES

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Abstract: We have performed petrological characterization and geochemical studies by instrumental neutron activation analysis of a suite of ten Yamato HED samples: Y-74013, Y-74097 and Y-74136 (Type A diogenites); Y-75032 and Y-791199 (Type B diogenites); Y-791195 (cumulate eucrite); Y-793164 and Y-82066 (eucrites); and Y-791192 and Y-82049 (polymict eucrites). The Type A diogenites are essentially identical in composition except for slight differences in Cr, Co, Se and La, which are likely due to inhomogeneous distribution of the minor phases chromite, metal and troilite, and trapped interstitial melt, respectively. The petrology and REE patterns for Type B diogenites show that they are not adcumulate rocks, but rather, contain substantial, perhaps 15%, interstitial liquid trapped in the samples. Y-791195 is a cumulate eucrite intermediate in REE content between Serra de Magé and Moore County, but is more ferroan. Eucrite Y-82066 is similar in composition to trace element-poor main-group eucrites such as Sioux County, and may be a primitive partial melt of the HED parent body. Y-793164 is intermediate in composition between main-group eucrites and Nuevo Laredo in Fe, Cr, Sc and REE, and is an intermediate member of the Nuevo Laredo trend eucrites. Y-793164 is a residual liquid from perhaps 25–30% crystallization of a primitive main-group eucrite like Sioux County or Y-82066. Y-791192 and Y-82049 are classified as polymict eucrites, but major and trace element concentrations indicate that these meteorites contain about 36% and 48% diogenitic material, respectively. These samples are howardites based on our analyses. Y-82049 contains a wide range of pyroxene compositions, from magnesian orthopyroxene similar to Type A diogenite pyroxenes, to ferroan pigeonite similar to basaltic eucrite pyroxenes. Large pyroxene clasts in Y-791192 are dominantly similar to Type B diogenite pyroxenes.

1. Introduction

Howardite, eucrite (monomict and polymict) and diogenite (HED) meteorites represent the most extensive suite of crustal magmatic rocks from differentiated asteroids. The basalts, cumulate gabbros and cumulate orthopyroxenites that make up these meteorites or occur as clasts within them provide the most detailed view of igneous processes on the small bodies of the solar system during its earliest epoch.

Basaltic eucrites are among the oldest igneous rocks known, with crystallization

ages of about 4.6 Ga (*e.g.*, NYQUIST *et al.*, 1986). Basaltic eucrites are frequently divided into the main-group, the Stannern trend and the Nuevo Laredo trend based on compositional differences. TAKEDA (1991) has used the term "ordinary eucrites" to describe these three eucrite groups based on mineralogic and petrographic criteria. This latter classification treats Pasamonte as a separate eucrite subtype, even though compositionally it is a main-group eucrite. Main-group eucrites have uniform mg# (molar $100 \cdot \text{MgO}/(\text{FeO} + \text{MgO})$) and incompatible refractory element contents and cluster on a diagram of TiO_2 vs. mg# (STOLPER, 1977). Typical main-group eucrites are Juvinas and Sioux County. Stannern trend eucrites have mg# similar to main-group eucrites, but have elevated incompatible element contents (STOLPER, 1977). Nuevo Laredo trend eucrites have lower mg# and elevated incompatible element contents compared to main-group eucrites (STOLPER, 1977; WARREN and JERDE, 1987). Although eucrites have been extensively studied, there is still considerable controversy regarding their origin. The most primitive main-group eucrites (those with the lowest contents of incompatible trace elements) have been considered to be residual melts from fractional crystallization of a totally molten asteroid (MASON, 1962), primary partial melts of a chondritic source region (STOLPER, 1977), residual melts formed from different regions of an HED asteroid magma ocean (IKEDA and TAKEDA, 1985), and residual liquids remaining after a primary partial melt crystallized to form diogenites (WARREN and JERDE, 1987). To date, there is no consensus on the origin of basaltic eucrites.

Cumulate rocks on the HED parent body include cumulate eucrites and diogenites. Cumulate eucrites are pigeonite-plagioclase gabbros, while diogenites are orthopyroxenites. Although there is a large compositional gap between these two lithologies, some intermediate cumulates are known which suggests that there may be a continuum of compositions. Binda is an orthopyroxene-plagioclase cumulate more magnesian than other cumulate eucrites (GARCIA and PRINZ, 1978), while the Yamato Type B diogenites (Y-75032-type) are low-Ca pyroxene-plagioclase cumulates more ferroan than typical diogenites (TAKEDA and MORI, 1985). Recently, polymict cumulate eucrite Y-791439 has been shown to contain a wide variety of mineral and lithic clasts extending from Type B diogenite-like to Moore County-like materials (SAIKI *et al.*, 1992; TAKEDA and HIDAHA, 1989).

As part of our broad study of HED meteorites, we have performed petrological characterization and geochemical studies of a representative suite of Yamato HED samples. The Antarctic meteorite collections of Japan and the United States represent a valuable source of HED meteorite samples, including types not present in the collections of non-Antarctic meteorites (TAKEDA, 1991). Hence, thorough study of these meteorites is expected to yield valuable insights into the differentiation of asteroid-sized bodies early in solar system history.

The purposes of our studies are to broaden the range of well characterized HED samples, and to further define igneous processes on the HED parent body. The samples we have studied are: diogenites Y-74013, Y-74097, Y-74136, Y-75032 and Y-791199; cumulate eucrite Y-791195; eucrites Y-793164* and Y-82066; polymict

* There are some data that suggest Y-793164 is paired with polymict eucrite Y-792769. Because none of our data indicate that Y-793164 is polymict, we will use the classification from YANAI and KOJIMA (1987) in this paper. This issue is discussed in more detail in Sections 3.3 and 4.3.

euclrites Y-791192 and Y-82049. We report here on our petrologic and geochemical study of these meteorites, and compare them with literature data and models on HED meteorites. Throughout this paper we will be comparing analyses of Yamato HED meteorites to means of other HED meteorites. These means are based on an extensive data compilation maintained by the senior author of HED meteorites containing virtually all modern analyses. As this compilation contains over 200 references, citation of the sources of the data is impractical and is not attempted.

2. Samples and Analytical Methods

We obtained whole rock chips of the diogenite samples from the National Institute of Polar Research. The diogenites were coarsely crushed in an agate mortar and pestle and the freshest interior material was hand-picked for instrumental neutron activation analysis (INAA). Small fragments of the diogenites were made into microprobe grain mounts for petrographic and mineral composition studies. The Type A diogenites (Y-74013-type) contained large, mm-sized chromite grains, which allowed chromite separates to be prepared for Y-74013 and Y-74136. The Type B diogenites (Y-75032-type) are composed of lithic clasts in dark gray to black glassy matrix. Y-75032 contained a small, pyroxene-plagioclase-chromite clast free of glassy matrix which was separated for INAA. A hand picked matrix-rich sample was also prepared. Because of the numerous mineral fragments mixed in the matrix, a pure matrix sample could not be obtained. For Y-791199, only a whole rock sample was prepared. Whole rock splits of Y-75032 and Y-791199 were separated for electron microprobe analysis (EMPA) on fused beads.

We obtained whole rock chips and thin sections of the euclrite samples from the National Institute of Polar Research. The samples appeared to be very fresh, with only minor iron oxide staining evident on some fragments. The samples were coarsely crushed in an agate mortar and pestle and splits were taken for INAA and EMPA on fused beads.

We performed INAA using the techniques and procedures in effect at Johnson Space Center (MITTLEFEHLDT and LINDSTROM, 1991). Irradiations are performed at the Research Reactor Facility of the University of Missouri. The diogenite samples were irradiated for 20 hours at a flux of $7.6 \times 10^{13} \text{ n/cm}^2 \cdot \text{s}$, while the euclrites were irradiated for 12 hours at a flux of $5.5 \times 10^{13} \text{ n/cm}^2 \cdot \text{s}$. The samples were counted three times at roughly 1/2, 1 and 3 weeks after irradiation to obtain data for nuclides of differing half-life. In addition, the diogenite samples were counted again about 3 months after irradiation to improve the data for trace elements with the longest-lived nuclides. The data reduction procedures used are described in MITTLEFEHLDT and LINDSTROM (1991) and MITTLEFEHLDT *et al.* (1992). The pure silica tubes we use to encapsulate samples contain a tiny amount of La. We therefore made blank corrections for La based on several analyses of empty silica tubes. The corrections are significant only for the Type A diogenites, and are; Y-74013–15%, Y-74097–19% and Y-74136–31%. Some Na is produced by the reaction $^{24}\text{Mg} (n, p) ^{24}\text{Na}$. We analyzed several samples of Specpure (“5–9 s”) MgO, fired at 800°C overnight to drive off any Na, in order to determine correction factors for Na *via* Mg. These corrections are

significant only for the diogenites and chromite separates, and are; Y-74013 wr-39%, cm-38%, Y-74097-40%, Y-74136 wr-38%, cm-14%, Y-75032 clast-4%, matrix-4%, Y-791199-5%. The MgO contents determined by EMPA were used for the corrections.

Whole rock splits of approximately 40 mg were finely ground and fused into a homogeneous glass using a Mo metal strip heater (BROWN, 1977). The Type A diogenites did not quench to glass, and could not be analyzed for major elements. The Type B diogenites, cumulate eucrite, eucrites and polymict eucrites all yielded homogeneous glass beads. These were analyzed by electron microprobe using 15 kV and 20 nA conditions with the electron beam rastered over an area of about 10 μm square. A sample of USGS standard rock BHVO-1 was prepared and analyzed using the same techniques as a control.

Mineral analyses were performed on a Cameca CAMEBAX electron microprobe at JSC. Pyroxene, olivine, chromite and ilmenite were analyzed using 20 kV, 40 nA, focused beam conditions to enhance excitation of the minor transition elements. Plagioclase analyses were performed using 15 kV, 20 nA, focused beam conditions. These conditions do not result in measurable volatilization of Na_2O and K_2O from the calcic plagioclases of HED meteorites. The JSC standard minerals collection provided the standardization base for the analyses. The Cameca PAP data reduction software was used to calculate concentrations, and drift correction was accomplished by normalizing to periodic analyses of the standards during the analytical sequence.

3. Results

Average pyroxene, plagioclase, chromite and ilmenite compositions are presented in Table 1. Average olivine compositions for Y-793164 are also presented, along with two individual olivine analyses for Y-82049. Pigeonites in HED meteorites have usually undergone subsolidus exsolution and inversion to produce augite lamellae from $<1 \mu\text{m}$ to $\sim 50 \mu\text{m}$ wide in a host of either lower calcium pigeonite or orthopyroxene (*e.g.*, TAKEDA and GRAHAM, 1991). The pyroxene data presented in Table 1 are therefore given as the best bulk pigeonite composition derived by averaging all spot analyses, plus an average of the most calcium-rich and calcium-poor spot analyses observed. For all the HED meteorites studied here, the calcic pyroxene occurs as exsolution lamellae rather than discrete grains. For the polymict eucrites, both an average of the most magnesian pyroxenes in the breccia, and average bulk pigeonite for the basaltic clasts are given. Approximate bulk compositions of individual pyroxenes are shown on pyroxene quadrilaterals in Fig. 1. Plagioclase compositions are shown on portions of orthoclase-albite-anorthite ternary diagrams in Fig. 2. Figure 3 shows variations in TiO_2 and Cr_2O_3 with mg# for chromites.

Major and trace element data obtained by EMPA on fused beads and by INAA are presented in Tables 2 and 3. Also listed in these tables are data on USGS standard rock BHVO-1 analyzed along with the HED samples, plus the recommended values for this standard. Major element data for BHVO-1 obtained by EMPA on fused beads agree well with the recommended values except for Na_2O which is low. We suspect that Na_2O volatilization occurred during preparation of the glass bead. There is good agreement between major elements determined on the fused beads and by INAA,

Table 1a. Average pyroxene compositions for Yamato HED meteorites. High Ca pyroxenes are exsolution lamellae in host low Ca pyroxenes.

	diogenite Type A		diogenite Type B		Y-791195,92-2			Y-82066,53-2		
	bulk	bulk	low Ca	high Ca	bulk	low Ca	high Ca	bulk	low Ca	high Ca
SiO ₂	54.5	53.1	53.1	53.2	50.3	49.9	51.1	50.2	49.8	51.5
TiO ₂	0.07	0.24	0.22	0.40	0.23	0.16	0.40	0.28	0.17	0.27
Al ₂ O ₃	0.54	0.58	0.55	0.85	0.33	0.27	0.68	0.35	0.26	0.50
Cr ₂ O ₃	0.66	0.29	0.24	0.41	0.15	0.11	0.28	0.36	0.26	0.25
FeO	15.7	20.7	21.4	8.8	28.0	32.6	15.5	26.4	33.7	16.5
MnO	0.53	0.67	0.67	0.36	0.90	1.05	0.50	0.82	1.00	0.53
MgO	26.7	23.0	23.3	15.7	12.9	13.6	11.2	12.0	13.6	10.5
CaO	1.07	1.58	0.85	20.4	7.3	2.34	20.4	9.5	1.19	20.1
sum	99.77	100.16	100.33	100.10	100.06	100.03	100.05	99.91	99.98	99.79
Wo	2.1	3.2	1.7	41.5	15.4	5.0	42.4	20.3	2.6	42.3
En	73.6	64.3	64.9	44.5	38.1	40.5	32.4	35.7	40.8	30.7
Fs	24.3	32.5	33.4	14.0	46.4	54.5	25.2	44.0	56.7	27.0

	Y-793164,63-3			Y-791192,91-1			Y-82049,61-3			
	bulk	low Ca	high Ca	breccia Mg-rich	basalt clast bulk	low Ca	high Ca	breccia Mg-rich	basalt clast 1 bulk	basalt clast 2 bulk
SiO ₂	48.5	48.2	49.3	53.5	50.1	49.7	51.5	55.1	50.0	49.1
TiO ₂	0.33	0.21	0.55	0.23	0.19	0.15	0.30	0.08	0.34	0.29
Al ₂ O ₃	0.59	0.52	0.58	0.51	0.33	0.14	0.56	0.73	2.05	0.33
Cr ₂ O ₃	0.61	0.83	0.64	0.26	0.13	0.08	0.19	0.65	0.78	0.67
FeO	32.2	36.4	24.5	21.2	29.8	36.1	15.7	14.5	24.0	31.2
MnO	0.98	1.11	0.72	0.70	0.89	1.06	0.48	0.48	0.75	1.00
MgO	9.4	9.7	9.0	23.2	12.0	12.4	10.6	27.8	17.1	12.6
CaO	6.9	2.83	14.3	1.17	6.9	0.89	20.9	1.10	5.1	4.7
sum	99.54	99.80	99.59	100.77	100.32	100.52	100.22	100.44	100.09	99.88
Wo	15.4	6.3	31.1	2.3	14.7	1.9	43.6	2.2	10.7	10.1
En	29.0	30.2	27.3	64.6	35.6	37.2	30.8	75.7	50.0	37.6
Fs	55.7	63.5	41.6	33.1	49.7	60.8	25.6	22.2	39.4	52.3

Table 1b. Average olivine composition for Y-793164 plus individual olivine analyses for Y-82049.

	Y-793164,63-3	Y-82049,61-3
SiO ₂	31.0	36.2
FeO	60.4	33.6
MnO	1.26	0.63
MgO	6.86	30.0
CaO	0.08	0.06
sum	99.60	100.49
Fo	16.8	61.4

Table 1c. Average plagioclase compositions for Yamato HED meteorites.

	diogenite Type B	Y-791195 ,92-2	Y-82066 ,53-2	Y-793164 ,63-3	Y-791192 ,91-1	Y-82049 ,61-3
SiO ₂	46.6	45.8	45.3	47.8	47.8	46.7
Al ₂ O ₃	35.2	35.8	35.9	33.7	34.1	34.4
FeO	0.30	0.25	0.19	0.57	0.67	0.54
CaO	17.9	18.6	18.6	16.4	17.4	17.5
Na ₂ O	1.23	1.00	0.79	1.64	1.35	1.24
K ₂ O	0.07	0.07	0.05	0.17	0.08	0.11
sum	101.30	101.52	100.83	100.28	101.40	100.49
Or	0.4	0.4	0.3	1.0	0.5	0.7
Ab	11.0	8.8	7.1	15.2	12.3	11.3
An	88.6	90.8	92.6	83.8	87.2	88.0

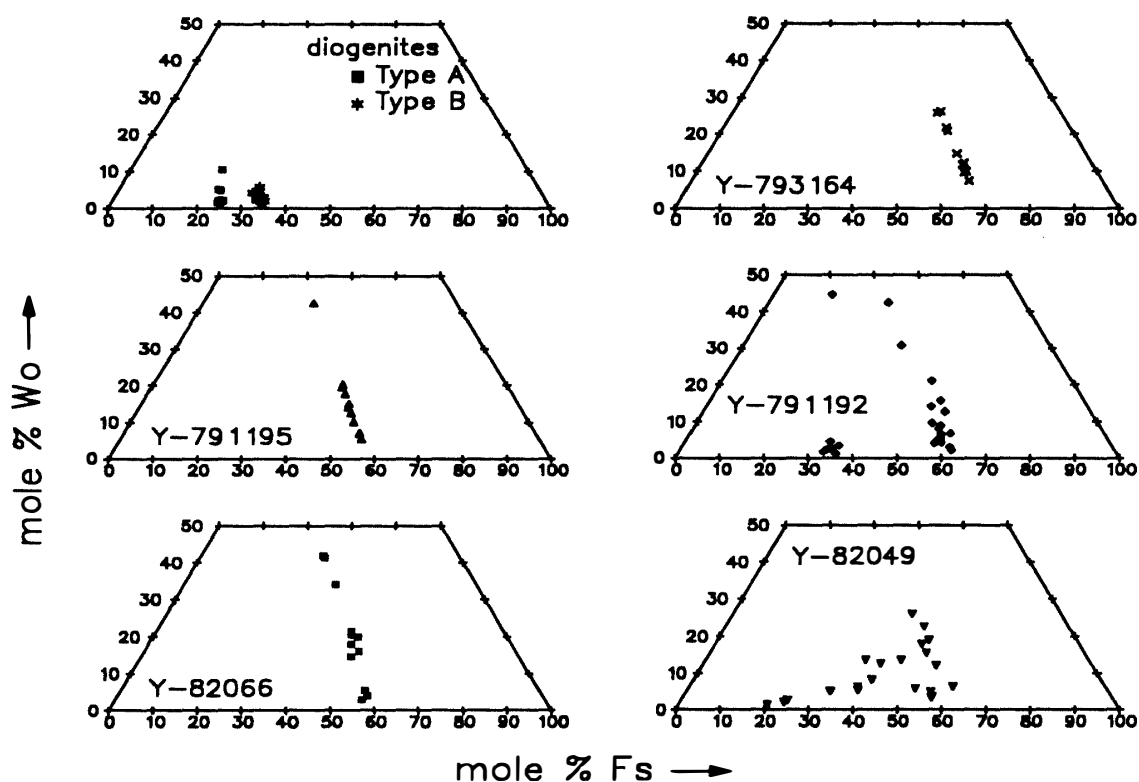


Fig. 1. Pyroxene quadrilaterals for Yamato HED meteorites.

except for low Na₂O for the Y-793164 glass bead. Again, we suspect volatilization. Our INAA data for BHVO-1 agree with the recommended values within uncertainties for all elements except Ni and Zr. Our data are low for both these elements.

3.1. Diogenites

Yamato diogenites have been divided into two petrologic categories; Type A or Y-74013-type and Type B or Y-75032-type, which are believed to represent only two

Table 1d. Average chromite and ilmenite compositions for Yamato HED meteorites.

	diogenite Type A		diogenite Type B		Y-791195,92-2		Y-82066 ,53-2	Y-793164 ,63-3	Y-791192,91-1				Y-82049,61-3		
	large cm	small cm	cm	ilm	cm	ilm*	ilm	ilm	breccia cm	basalt clast cm	breccia ilm	basalt clast ilm	breccia cm	basalt clast cm	basalt clast ilm
TiO ₂	0.75	0.86	1.88	52.9	11.9	51.6	52.0	51.5	4.61	2.47	53.1	52.5	2.46	4.10	51.6
SiO ₂	0.02	0.07	0.04	—	0.03	—	0.02	0.05	0.04	0.10	0.16	—	0.13	0.10	0.11
Cr ₂ O ₃	59.9	54.7	54.4	0.73	39.1	1.75	0.08	0.06	49.0	50.4	0.82	0.13	51.8	49.5	0.11
Al ₂ O ₃	7.67	9.26	8.44	0.03	5.02	0.03	0.01	0.01	8.20	10.2	0.11	0.12	9.11	7.09	0.04
V ₂ O ₃	0.61	0.58	0.59	—	0.76	—	—	—	0.51	0.68	—	—	0.58	0.73	—
⁺ Fe ₂ O ₃	0.34	1.90	0.48	0.62	0.82	0.53	0.94	0.90	0.96	0.58	0.09	0.73	0.68	1.37	1.10
FeO	24.6	26.2	31.2	41.1	41.5	44.2	44.7	44.9	34.1	32.9	42.4	44.5	32.6	33.6	42.8
MnO	0.45	1.09	0.53	1.20	0.60	0.90	0.94	0.90	0.54	0.53	0.75	0.91	0.52	0.55	0.94
MgO	5.89	4.40	2.08	3.23	0.98	1.36	0.78	0.50	1.83	1.19	2.85	1.22	1.71	1.56	1.68
CaO	—	0.04	0.09	0.06	0.06	0.03	0.11	0.10	0.07	0.12	0.11	0.08	0.07	0.04	0.31
sum	100.23	99.10	99.73	99.87	100.77	100.40	99.58	98.92	99.86	99.17	100.39	100.19	99.66	98.64	98.69
mg#	29.9	23.0	10.6	12.3	4.0	5.2	3.0	1.9	8.7	6.1	10.7	4.7	8.5	7.6	6.5
cr#	84.0	79.8	81.2	—	83.9	—	—	—	80.0	76.8	—	—	79.2	82.4	—

⁺ Fe₂O₃ calculated according to the procedures of CARMICHAEL (1967).

* Exsolution lamella in chromite.

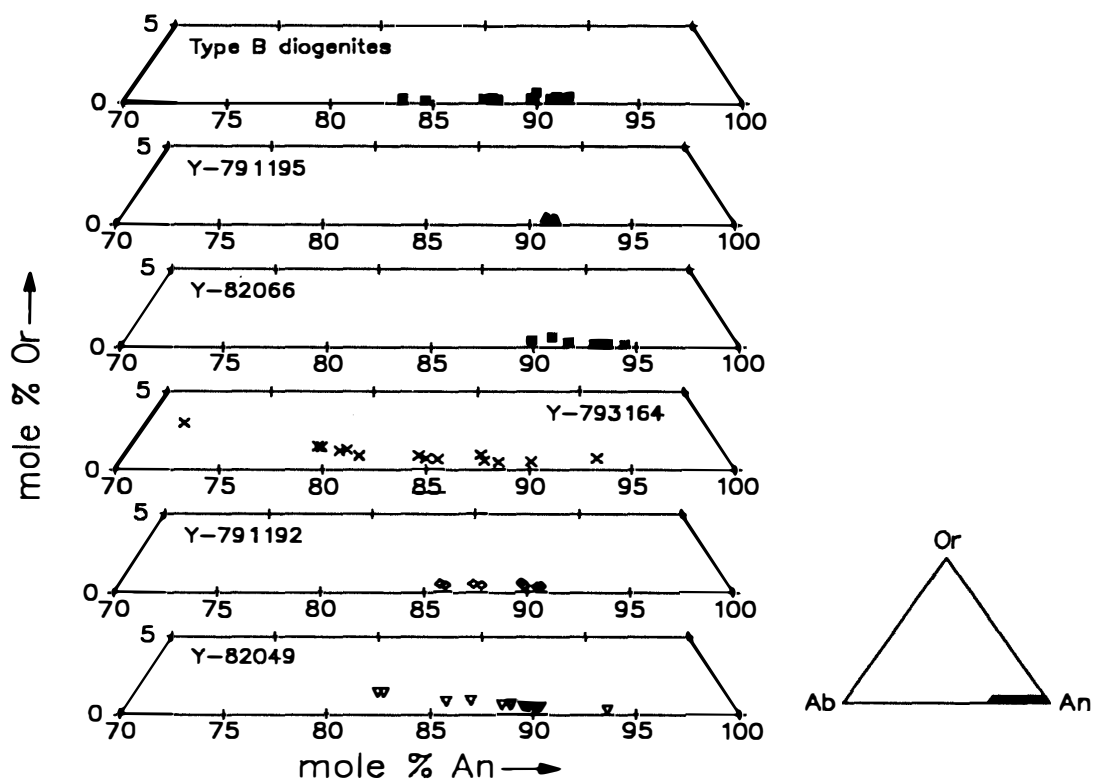


Fig. 2. Portions of the plagioclase ternary diagram (insert) for Yamato HED meteorites.

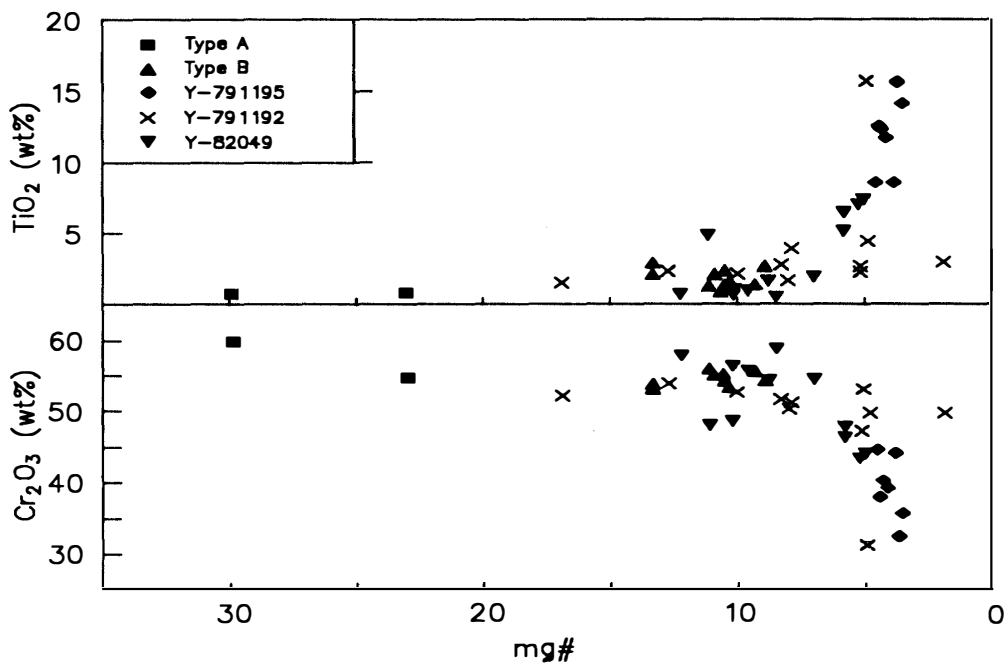


Fig. 3. TiO_2 and Cr_2O_3 vs. mg# for chromites of Yamato HED meteorites.

Table 2. Major element composition of Yamato HED meteorites determined by fused-bead electron microprobe analysis.

	Y-75032	Y-791199	Y-791195	Y-82066	Y-793164	Y-791192	Y-82049	BHVO-1	
	,79	,79	,75	,63	,69	,95	,75	JSC	G&R*
SiO ₂	52.9	52.8	49.3	48.9	48.8	50.2	49.6	49.4	49.9
TiO ₂	0.26	0.24	0.25	0.54	0.94	0.34	0.41	2.82	2.71
Al ₂ O ₃	3.4	3.1	13.3	13.9	12.3	10.2	8.3	13.7	13.8
Cr ₂ O ₃	0.69	0.77	0.34	0.30	0.31	0.66	0.79	0.05	0.04
FeO	18.6	18.7	17.3	17.8	19.7	17.1	17.8	10.9	11.0
MnO	0.61	0.60	0.58	0.54	0.58	0.54	0.54	0.17	0.17
MgO	20.9	20.9	7.7	7.2	5.8	13.9	15.2	7.1	7.23
CaO	3.61	3.53	10.5	10.3	10.6	7.5	6.6	11.6	11.4
Na ₂ O	0.10	0.10	0.40	0.43	0.30 ⁺	0.28	0.22	2.0 ⁺	2.26
K ₂ O	—	0.03	0.03	0.04	0.04	0.03	—	0.48	0.52
P ₂ O ₅	—	—	—	0.05	—	—	0.04	0.24	0.27
sum	101.07	100.77	99.70	100.00	99.37	100.75	99.50	98.46	99.30
mg#	66.7	66.6	44.2	41.9	34.4	59.2	60.3		

* GLADNEY and ROELANDTS (1988).

⁺ Na₂O appears to be low, probably due to volatilization during preparation of the glass bead.

falls (TAKEDA *et al.*, 1981; TAKEDA, 1991). Type A diogenites are granular, recrystallized orthopyroxenites as typified by the first diogenite recovered from Antarctica, Y-692 (OKADA, 1975; OKADA *et al.*, 1975; TAKEDA *et al.*, 1975). Our samples of Type A diogenites are typical of the fine-grained regions of these meteorites with orthopyroxene grains about 100 μ m across containing abundant inclusions predominantly of troilite (TAKEDA *et al.*, 1981). However, the mm-sized chromite grains obtained from Y-74013 and Y-74136 show that a portion of our samples consisted of coarse-grained material. The Type A diogenites have pyroxene compositions (Fig. 1 and TAKEDA *et al.*, 1981) identical to normal diogenites such as Johnstown (*e.g.* FLORAN *et al.*, 1981). The two Ca-rich pyroxenes in the Type A diogenites (Fig. 1) are tiny pyroxene inclusions in mm-sized chromites. No plagioclase was found in our grain mounts of the Type A diogenites.

Type B diogenites are brecciated pigeonite-plagioclase rocks petrologically intermediate between normal diogenites and cumulate eucrites, and are typified by Y-75032 (TAKEDA and MORI, 1985). The mineralogy and texture of Y-75032 and Y-791199 have been described previously (TAKEDA *et al.*, 1979; TAKEDA and MORI, 1985). The matrix of the Type B diogenites is black, glassy material composed of devitrified shock melt plus small clastic debris. These diogenites have more ferroan pyroxenes than any other diogenite (Fig. 1 and TAKEDA and MORI, 1985). Plagioclase compositions for the Type B diogenites vary from about An₈₃ to An₉₂ (Fig. 2), although TAKEDA and MORI (1985) report plagioclase compositions as sodic as An₇₅. Our samples of Y-75032 and Y-791199 contain ilmenite, and we found a silica polymorph in Y-75032. These phases have not previously been described for Type B diogenites.

The three Type A diogenites, Y-74013, Y-74097 and Y-74136, are essentially identical in composition except for slight differences in Cr, Co, Se and La (Table 3). The REE data for the Type A diogenites are shown in Fig. 4, compared with a range

Table 3. INAA data on Yamato HED meteorites.

		Type A diogenites					Type B diogenites		
		Y-74013	Y-74013	Y-74097	Y-74136	Y-74136	Y-75032	Y-75032	Y-791199
		,68	,68	,98	,71	,71	,79	,79	,79
		wr	cm	wr	wr	cm	clast	matrix rich	wr
weight	mg	42.72	7.40	67.06	35.18	13.27	43.89	40.99	47.09
Na ₂ O	wt%	0.0073	0.0017	0.0075	0.0078	0.0153	0.090	0.080	0.070
K ₂ O	wt%				0.0016	0.016	0.006	0.007	0.026
CaO	wt%	1.2		1.2	0.9		3.9	3.7	3.1
Sc	μg/g	11.4	4.9	11.2	10.9	4.9	20.8	21.1	21.1
Cr ₂ O ₃	wt%	0.732	60.8	0.702	0.693	57.3	0.618	0.646	0.732
FeO	wt%	16.8	25.6	15.2	16.8	24.5	17.9	18.2	18.2
Co	μg/g	27.4	45	9.5	34.1	39	14.0	16.2	11.0
Ni	μg/g				33			20	
Zn	μg/g	3.4		24	4	14			
Se	ng/g	950			1200		400	400	400
Br	ng/g	60	200		40		100	60	
Sr	μg/g								
Zr	μg/g								
Sb	ng/g								
Ba	μg/g						20		13
La	μg/g	0.014		0.006	0.007		0.208	0.40	0.48
Ce	μg/g						0.9	0.5	2.0
Nd	μg/g								
Sm	μg/g	0.011		0.0094	0.009		0.216	0.367	0.276
Eu	μg/g	0.003					0.111	0.110	0.081
Tb	μg/g						0.08	0.11	0.10
Yb	μg/g	0.08		0.073	0.07		0.54	0.64	0.54
Lu	μg/g	0.013		0.012	0.014		0.077	0.088	0.087
Hf	μg/g						0.15	0.31	0.32
Ta	ng/g							50	40
Ir	ng/g								
Th	ng/g								
U	ng/g								

for 16 samples of the EETA79002 diogenite (MITTFELDLT and MEYERS, 1991). Our three samples of Type A diogenites show a narrower range in REE content, excluding La, than the 16 samples of EETA79002. Our REE analyses of Type A diogenites agree well with those of MASUDA and TANAKA (1978) and MASUDA *et al.* (1979) except that our samples have lower La contents. Our La data range from 0.006–0.014 μg/g, while those of MASUDA and TANAKA (1978) and MASUDA *et al.* (1979) range from 0.016 to 0.0741 μg/g. The Type A Yamato diogenites are geochemically similar to the majority of Antarctic and non-Antarctic diogenites.

The Type B diogenites, Y-75032 and Y-791199, are richer in incompatible trace elements than the Type A diogenites, as illustrated in Fig. 4. The matrix-rich sample of Y-75032 has higher concentrations of the most incompatible elements than does the

Table 3 (Continued).

		cumulate eucrite	basaltic eucrites		polymict eucrites		standard	
		Y-791195	Y-82066	Y-793164	Y-791192	Y-82049	BHVO-1	
		,75 wr	,63 wr	,69 wr	,95 wr	,75 wr	JSC	G&R*
weight	mg	95.26	89.25	88.19	81.15	99.27	26.63	
Na ₂ O	wt%	0.393	0.422	0.545	0.292	0.253	2.37	2.26
K ₂ O	wt%	0.034	0.032	0.06	0.029	0.020	0.49	0.52
CaO	wt%	10.1	10.2	10.3	7.3	6.2	11.7	11.4
Sc	µg/g	30.4	29.3	33.6	21.8	22.9	31.6	31.8
Cr ₂ O ₃	wt%	0.308	0.308	0.301	0.681	0.798	0.0447	0.042
FeO	wt%	17.2	18.4	19.7	16.7	17.8	11.5	11.0
Co	µg/g	6.2	7.1	5.9	12.0	21.4	47.1	45
Ni	µg/g					130	90	121
Zn	µg/g						113	105
Se	ng/g		600		800	400		
Br	ng/g	80		260				
Sr	µg/g	100	60	70	60	30	450	400
Zr	µg/g			60		40	110	180
Sb	ng/g	17					140	160
Ba	µg/g		30	50	20	18	150	140
La	µg/g	0.49	2.13	3.45	0.80	1.55	16.5	15.8
Ce	µg/g	1.8	5.3	10.5	3.2	3.1	40.2	39
Nd	µg/g			7		4	28	25
Sm	µg/g	0.407	1.45	2.35	0.57	0.99	6.7	6.2
Eu	µg/g	0.44	0.58	0.72	0.40	0.33	2.21	2.1
Tb	µg/g	0.14	0.34	0.54	0.16	0.25	1.06	1.0
Yb	µg/g	0.58	1.63	2.28	0.78	0.98	2.16	2.0
Lu	µg/g	0.090	0.25	0.35	0.122	0.150	0.28	0.29
Hf	µg/g	0.57	0.89	1.67	0.44	0.68	4.7	4.4
Ta	ng/g	20	140	220	50	100	1240	1200
Ir	ng/g					3.8		
Th	ng/g	110	270	400	40	110	1240	1100
U	ng/g	640 ⁺	70	120			520	420

Uncertainty in the data are ≤ 7 in the least significant digit.

* GLADNEY and ROELANDTS (1988).

⁺ U in Y-791195 is too high compared to other incompatible elements such as La. We suspect contamination, probably by U in the Antarctic environment.

lithic clast sample; La and Hf are about 2 times higher in the matrix-rich sample compared to the lithic clast. The less incompatible elements Yb and Lu are only about 15% higher in the former, and Sc, which is compatible in pyroxene, is identical in the matrix and lithic clast samples. Our REE data for the Type B diogenites are systematically lower than those of SHIMIZU and MASUDA (1981) for Y-75032. Compared to our Y-75032 clast REE data, SHIMIZU and MASUDA's (1981) REE data are 3.4 times higher for La and 1.4 times higher for Lu. Our Eu datum agrees well with that of SHIMIZU and MASUDA (1981).

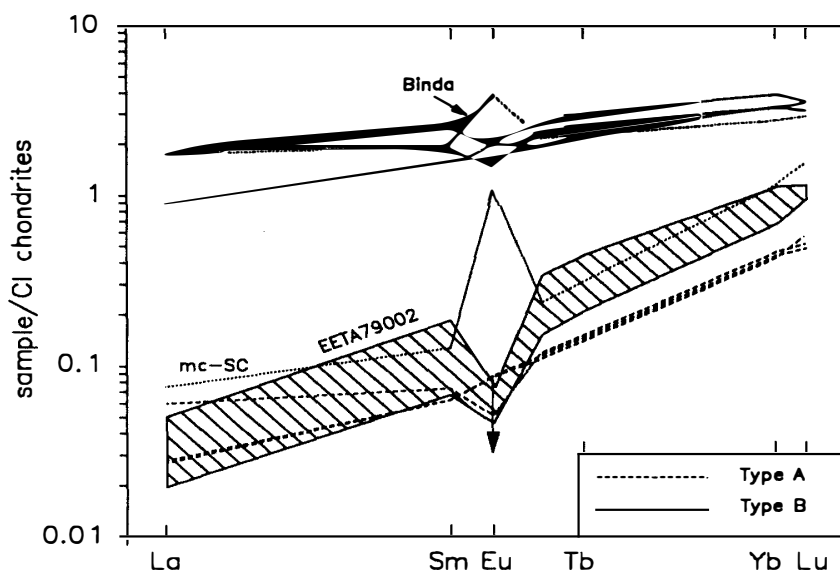


Fig. 4. REE diagram for Yamato diogenites. The Binda eucrite (MITTLEFEHLDT, 1979) and a field for 16 samples of EETA79002 (MITTLEFEHLDT and MEYERS, 1991) are shown for comparison. Also shown is a calculated model Type B diogenite accumulate assuming a parent melt with REE similar to Sioux County (mc-SC) (see text).

3.2. Cumulate eucrite

Y-791195 is classified as a cumulate eucrite in YANAI and KOJIMA (1987). It is a medium-grained, equigranular, unbrecciated rock with mean pyroxene and plagioclase grain sizes of about 0.5 mm (see also TAKEDA, 1991, Fig. 2). Relatively large, 0.2–0.3 mm, grains of a silica polymorph are also present. Y-791195 is finer-grained than the cumulate eucrite Moore County, which has a grain size of 0.5–2.5 mm (HESS and HENDERSON, 1949), but is only slightly finer-grained than Moama, which has a grain size in the range 0.5–1 mm (LOVERING, 1975). Our pyroxene analyses of Y-791195 are shown in Fig. 1, and are similar to the distribution of pyroxenes presented in YANAI and KOJIMA (1987). Mean pyroxene in Y-791195 has an mg# of 45, and is more ferroan than either Serra de Magé (mg# 56, HARLOW *et al.*, 1979), or Moore County (mg# 55, MITTLEFEHLDT, 1990) pyroxenes. Y-791195 whole rock composition also has a lower mg# (44.2, Table 2) than either Serra de Magé (mg# 55.6), or Moore County (mg# 49.3) (MCCARTHY *et al.*, 1973). Chromites in Y-791195 have very low mg# (~ 4) and high ulvöspinel contents (Fig. 3). Plagioclase compositions for Y-791195 are remarkably uniform (Fig. 2) at $\sim \text{An}_{91}$. The plagioclase data given in YANAI and KOJIMA (1987) indicate that there is a wider range in plagioclase compositions in Y-791195 than we found, however. The REE data for Y-791195 are compared to other cumulate eucrites in Fig. 5. The REE pattern of Y-791195 shows that it is indeed similar to cumulate eucrites in composition, and is intermediate between Serra de Magé and Moore County in REE content, the two most incompatible-element-rich cumulate eucrites.

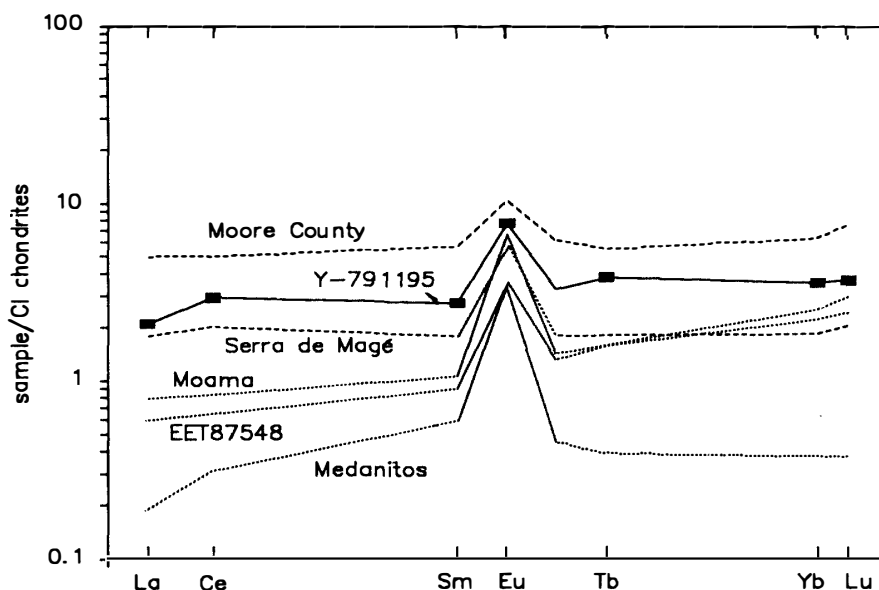


Fig. 5. REE diagram for Y-791195 compared to other cumulate eucrites.

3.3. Eucrites

Eucrite Y-82066 is a coarse-grained, brecciated eucrite with grain size of about 1–1.5 mm. Our thin section contains numerous, several mm-sized igneous clasts in a fine-grained fragmental matrix. The pyroxene compositions in Y-82066 are similar to those of the main-group eucrites, with an average mg# of 45 (Fig. 1). Plagioclase compositions are more variable than for cumulate eucrite Y-791195, and are more calcic on average, \sim An₉₃ (Fig. 2). Our pyroxene and plagioclase analyses of Y-82066 agree well with those in YANAI and KOJIMA (1987), except that we did not find any of the more sodic plagioclases. Y-793164 is a fine-grained breccia containing numerous mineral clasts, but few lithic clasts. The largest mineral clasts are about 0.5 mm across. The matrix is very fine-grained and well sintered, and appears to be identical to that of polymict eucrite Y-792769 (TAKEDA, 1991). Pyroxenes in Y-793164 are more ferroan than those in typical eucrites, with an average mg# of \sim 34 (Fig. 1). Tiny fayalitic olivines (\sim Fo₁₇, Table 1) occur in Y-793164 interstitial to pyroxene and plagioclase, and associated with Mg-poor ilmenite (mg# 1.9, Table 1). Plagioclase is quite variable, An_{93–72} and more sodic, mean \sim An₈₄ (Fig. 2), than those in Y-791195 or Y-82066. Our pyroxene, plagioclase and olivine analyses of Y-793164 agree well with those in YANAI and KOJIMA (1987), except that we did not find any of the more magnesian pyroxenes shown by them. Our sample of Y-793164 shows no mineralogical evidence that it is polymict.

Y-82066 is similar in bulk composition to main-group eucrites such as Sioux County, while Y-793164 is more similar to the evolved eucrites Lakangaon and Nuevo Laredo. Figure 6 shows the compositions of Y-82066 and Y-793164 normalized to mean Sioux County for a range of elements. For comparison, mean Stannern and Lakangaon are also shown. As can be seen, many elements in Y-82066 are within analytical error of mean Sioux County (horizontal line). However, Y-82066 is slightly more magnesian (mg# 41.9, Table 2) than Sioux County (mean mg# 40.6). Although

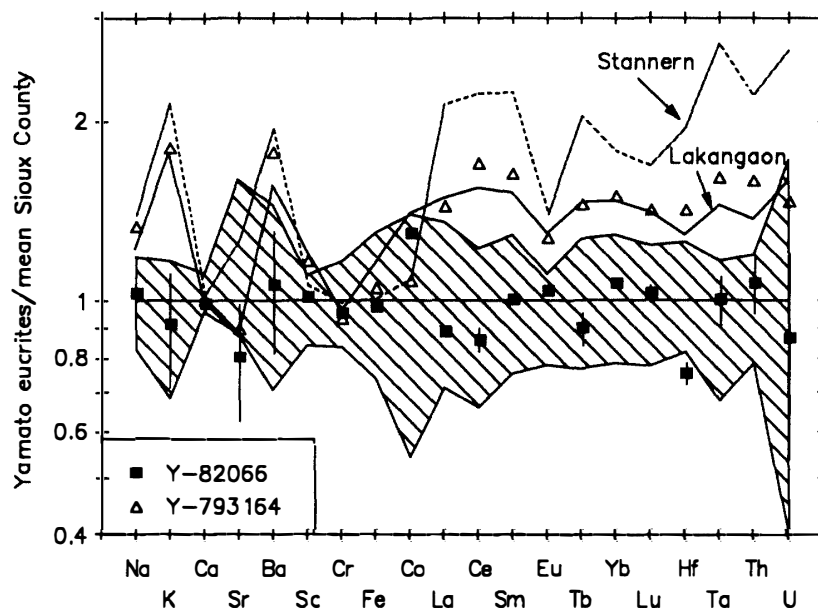


Fig. 6. Y-82066 and Y-793164 normalized to mean Sioux County for various elements. The diagonally ruled field represent the range of analyses for Sioux County samples. Mean Lakangaon and Stannern are shown for comparison.

Y-793164 is generally similar to Lakangaon, it is slightly less ferroan; mg# of Y-793164 is 34.4 (Table 2) vs. a mean of 32.3 for Lakangaon. Again, our sample of Y-793164 shows no compositional evidence that it is polymict. However, bulk compositional data would not necessarily allow for an easy distinction between monomict and polymict eucrites. It may be that Y-793164 is a polymict eucrite, but if so, it is dominated by evolved eucritic compositions similar to Lakangaon and Nuevo Laredo.

3.4. Polymict eucrites

We have analyzed two HED samples that are classified as polymict eucrites, Y-791192 and Y-82049. Polymict eucrites are eucritic breccias which can contain up to 10% material from other lithologic units (DELANEY *et al.* 1983). Y-82049 is a fragmental breccia, while Y-791192 contains abundant dark glass in the matrix. Pyroxenes in Y-82049 vary from typical diagenitic orthopyroxenes with mg# of 80–75 up to ferroan pigeonites typical of basaltic eucrites (Fig. 1). The pyroxene distribution in Y-791192 is more unusual. Pyroxenes in the basaltic clasts are similar to basaltic eucrite pyroxenes, while all of the larger pyroxene fragments we measured in the breccia are identical to Type B diagenite pyroxenes (Fig. 1). Plagioclase compositions in Y-82049 vary from An_{94-83} , while those in Y-791192 range from An_{90-85} (Fig. 2). Two olivines in Y-82049 have compositions of Fo_{61} and Fo_{56} (Table 1). Our pyroxene and plagioclase analyses for Y-791192 and Y-82049 agree well with those presented in YANAI and KOJIMA (1987), except that these authors show a wider range in plagioclase compositions in Y-791192 than we found.

Among the elements we determine by INAA, Ca and Eu are sensitive indicators of the relative amounts of eucritic and diagenitic material in the polymict breccias; Ca

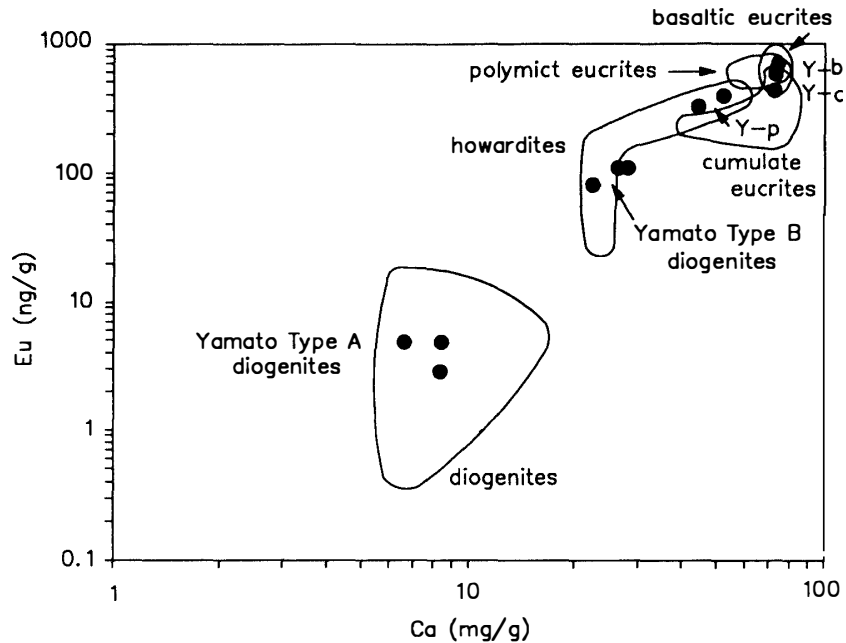


Fig. 7. *Eu vs. Ca for HED samples comparing Yamato HEDs from this study with fields for basaltic eucrites, cumulate eucrites, polymict eucrites, howardites and diogenites. Y-p are polymict eucrites Y-791192 and Y-82049, Y-b are basaltic eucrites Y-793164 and Y-82066, Y-c is cumulate eucrite Y-791195.*

is about 8 times and Eu about 50 times more abundant in eucrites than in diogenites. Figure 7 is a plot of Eu vs. Ca for mean eucrites, polymict eucrites, howardites and diogenites and the Yamato HED samples from this study. The two polymict eucrite samples, Y-791192 and Y-82049, plot between the fields of basaltic eucrites and diogenites, and outside the field of polymict eucrites.

4. Discussion

4.1. Diogenites

As noted above, there are slight differences in Cr, Co and Se among the three Type A diogenites we analyzed (Table 3). These differences are likely due to inhomogeneous distribution of the minor phases chromite, metal and troilite. In addition, Y-74013 has a slightly higher La content than Y-74097 or Y-74136.

The Type B diogenites are suggested to be cumulates intermediate in composition between normal diogenites and cumulate eucrites, possibly forming a single fractional crystallization trend (TAKEDA and MORI, 1985). The higher incompatible trace element contents of the Type B diogenites (Y-75032 and Y-791199) compared to the Type A diogenites (Fig. 4), and their more ferroan pyroxenes (Fig. 1), are broadly consistent with this model. However, the large enrichment in the most incompatible elements in Type B diogenites as compared to Type A diogenites indicates that this model is too simple. For example, the mean La content of Type B diogenites, $\sim 0.36 \mu\text{g/g}$, is a factor of 40 times that of mean Type A diogenites, $\sim 0.009 \mu\text{g/g}$. This difference cannot be due to crystal fractionation alone, as a 40 fold increase in La would require $\geq 97.5\%$

crystallization of the parent melt of the diogenites, assuming constant partition coefficients. This amount of fractional crystallization would result in more extreme variations in mineralogy and mineral compositions than are observed. Hence, it is impossible for the Type A and B diogenites to both be *adcumulates* from a single parent magma. For comparison, the REE pattern for Binda (MITTFELDLT, 1979), the cumulate eucrite closest in mineralogy to the Type B diogenites (TAKEDA and MORI, 1985), is shown.

The petrology of Y-75032 demonstrates that this diogenite is not an *adcumulate*. TAKEDA and MORI (1985) have shown that plagioclase in Y-75032 exhibits a strong Na-enrichment trend from $\sim\text{Ab}_{10}$ to $\sim\text{Ab}_{25}$, while pyroxenes have uniform mg# of about 66. They interpreted this trend as indicating that plagioclase crystallized from trapped intercumulus liquid. The presence of ilmenite in Y-75032 and Y-791199 and a silica polymorph in Y-75032 also show that intercumulus melt was trapped in Type B diogenites. Pyroxenes in Type B diogenites are similar in mg# to liquidus pyroxenes produced in melting experiments on Sioux County (STOLPER, 1977). Hence, Type B diogenites could have formed from a parent melt similar to Sioux County. In Sioux County, however, a silica phase appears only after about 70% of the melt has crystallized (STOLPER, 1977; Figs. 2 and 3). Therefore, the silica in Type B diogenites must have formed late from a trapped liquid. Similarly, ilmenite is commonly a late phase in eucrites, occurring in interstitial regions, and its presence in Y-75032 and Y-791199 also suggests that trapped liquid is present in Type B diogenites.

The REE patterns of the Type A diogenites approximate that of a pure orthopyroxene *adcumulate*. Using orthopyroxene/melt partition coefficients calculated by the method of COLSON *et al.* (1988), we can match the Yb and Lu in Type A diogenites as pure *adcumulates* from a melt with ~ 3.2 times CI chondrites REE. Sioux County has the lowest REE content, 10 times CI chondrites, among the basaltic eucrites. This is 3 times the REE content of a model parent melt for the Type A diogenites. Assuming equilibrium melting, this difference implies that the parent melt for the Type A diogenites is 3 times the fraction of the source region that Sioux County is. That is, if Sioux County represents 15% partial melting of the HED parent body (CONSOLMAGNO and DRAKE, 1977), then the parent melt for the Type A diogenites represents 45% partial melting. Because of uncertainties in orthopyroxene/melt partition coefficients, however, we don't believe the degree of partial melting required for a Type A diogenite parent melt can be quantified. Nevertheless, the Type A diogenite parent melt must be a more extensive partial melt than basaltic eucrites because of the low REE contents and high mg# of the Type A diogenites. Lanthanum in the Type A diogenites is too high for a pure *adcumulate*, but only between 0.6–1.7% trapped liquid in the samples could account for the difference.

In agreement with petrologic observations, the REE patterns for Type B diogenites show that these samples are not *adcumulate* rocks. Figure 4 shows the REE patterns for a model pyroxene-plagioclase *adcumulate* compared to the Type B diogenites. We calculated the model *adcumulate* as follows: We estimated that our Type B diogenite samples contain between 8–14% plagioclase based on the Ca content of our bulk samples (Table 3) and average mineral compositions (Table 1). We used 10% plagioclase and 90% pyroxene for the model *adcumulate*. We used the pyroxene

and plagioclase REE partition coefficients of MCKAY *et al.* (1986) and WEILL and MCKAY (1975), respectively. We assumed the parent melt was similar to eucrites that may be unevolved, primary partial melts, such as Sioux County. We used the mean REE contents of Sioux County to generate model adcumulates. As can be seen (Fig. 4), an adcumulate composed of 90% pigeonite and 10% plagioclase would have a light REE content an order of magnitude lower than measured in Type B diogenites, and should have a large positive Eu anomaly.

The difference between the Type B diogenite samples and the model adcumulate indicates that either the parent melt of the Type B diogenites was LREE-enriched and had a negative Eu anomaly, or, more likely, that the Type B diogenites contain a component of interstitial liquid trapped in the sample. This latter model is compatible with petrologic observations of Na-enrichment in plagioclase (TAKEDA and MORI, 1985) and the presence of a silica polymorph and ilmenite as discussed above. Based on the simple model presented above, only about 15% interstitial liquid would need to be trapped in Type B diogenites to generate the observed REE patterns from the model adcumulate pattern. However, the actual amount of trapped liquid cannot be accurately calculated because of the large number of assumptions involved in the calculation.

Because pyroxenes in Type B diogenites are similar in composition to liquidus pyroxenes in experiments on Sioux County, the parent melt for Type B diogenites was probably similar to basaltic eucrites. The Type B diogenites have little, if any cumulus plagioclase (TAKEDA and MORI, 1985), and therefore plagioclase was not a liquidus phase. These features of Type B diogenites suggest that their parent melt was likely a slightly higher degree melt of the source region than main-group eucrites, such that the melt composition had left the eucrite peritectic and was located on the olivine-pyroxene reaction boundary (*see* STOLPER, 1977). Because of the trapped liquid component in Type B diogenites, we cannot use the incompatible trace element contents to test this model. Similarly, the trapped melt component precludes our attempting to determine the relationship between Types A and B diogenites.

As noted above, the lithic clast sample of Y-75032 has lower concentrations of the most highly incompatible elements than does the matrix-rich sample, and is lower in REE than the whole rock Y-75032 samples of SHIMIZU and MASUDA (1981). These differences are consistent with minor increases in the amount of interstitial melt component in the glassy matrix and whole rock samples. Because these meteorites are breccias, however, the higher incompatible trace element contents of the glassy matrix and whole rock samples could be due to foreign contaminants that might have been introduced into the breccias by impacts. Some of the Type B diogenites do contain pyroxenes with compositions similar to cumulate eucrites (*e.g.*, *see* Y-791073 and Y-791201 in YANAI and KOJIMA, 1987), and therefore there is a cumulate eucrite component in some Type B diogenite breccias. Because cumulate eucrites generally have REE contents similar to those we found for the Y-75032 lithic clast, cumulate eucrite contamination would have only a very minor affect on Type B diogenite whole rock REE concentrations. We have found no pyroxenes with ferroan pigeonite compositions typical of basaltic eucrites in our Type B diogenite samples, nor are basaltic eucrite pyroxenes evident in the pyroxene data shown by YANAI and KOJIMA

(1987). The Type B diogenite Y-791439 contains ferroan pyroxenes similar to those of basaltic eucrites (YANAI and KOJIMA, 1987), hence basaltic contamination in the glassy matrix cannot be ruled out. Impact processes are not likely to have preferentially destroyed all fragments of basaltic material in Type B diogenites, however. Lacking mineralogic evidence for a basaltic component in Y-75032 and Y-791199, we believe it unlikely that basaltic contaminants were incorporated into the matrix glass of these meteorites. Regardless, the clast sample of Y-75032 was hand picked free of matrix glass, and cannot be contaminated.

4.2. Cumulate eucrite

The medium-grained, equigranular texture of Y-791195 is consistent with its being a cumulate, although one that cooled faster than typical cumulate eucrites such as Moore County. Faster cooling is also suggested by the generally thinner pyroxene exsolution lamellae in Y-791195 as compared to Moore County (*e.g.*, see TAKEDA, 1991; TAKEDA *et al.*, 1988). The REE pattern of Y-791195 indicates that it is indeed a cumulate eucrite. Y-791195 is more ferroan than either Serra de Magé or Moore County, the two most ferroan cumulate eucrites. The average spinel composition for Y-791195 has lower mg# (4.0) and Cr₂O₃ content (39.1 wt%) and higher TiO₂ content (11.9 wt%) than do spinels from either Serra de Magé (mg# 6.5, Cr₂O₃ 53.0 wt%, TiO₂ 3.2 wt%) or Moore County (mg# 5.5, Cr₂O₃ 42.3 wt%, TiO₂ 10.1 wt%) (BUNCH and KEIL, 1971). Spinel crystallizing from a differentiating basaltic melt will evolve to lower mg# and Cr₂O₃ contents and higher TiO₂ contents (*e.g.*, HILL and ROEDER, 1974). Therefore, Y-791195 originated from a more evolved melt than the latter two cumulate eucrites. However, Y-791195 is lower in incompatible trace element contents, as exemplified by the REE, than Moore County (Fig. 5). This apparent contradiction could be caused by heterogeneity in trace element distribution. For example, the La concentration in Serra de Magé varies from 0.257 to 0.58 µg/g (MA and SCHMITT, 1979; PALME *et al.*, 1978), a factor of 2.3 times. However, 5 analyses of REE in Moore County vary by only about 30%, and it is unlikely that sample heterogeneity can explain the higher REE content of Moore County relative to the more ferroan Y-791195. The differences in REE content could also be due to differences in the amount of crystallized trapped liquid in the cumulates. The higher REE content of Moore County relative to Y-791195 would then suggest that the former contains a substantial amount of crystallized trapped magma. These arguments assume that the cumulate eucrites were formed from similar parent melts. An alternative model would have Moore County crystallizing from a trace element-rich primitive parent magma, similar to Stannern.

WARREN and KALLEMEYN (1992) have suggested that Y-791195 is a cumulate from a Nuevo Laredo trend parent melt. Our data generally agree with this conclusion. Bulk pyroxene in Y-791195 has an mg# of 45 (Table 1), and using the pigeonite-liquid K_D (Fe/Mg) of STOLPER (1977), we calculate that a melt in equilibrium with Y-791195 would have an mg# of ~20. This is much lower than those of Lakangaon and Nuevo Laredo (~33) and indicates that Y-791195 last equilibrated with a highly evolved melt. This is also born out by the Sc and La contents of Y-791195, which suggest that it may be a cumulate from a primitive (Sioux County-like) eucritic basalt after about

80% crystallization has occurred (Fig. 8). The presence of relatively large grains of a silica polymorph in Y-791195 is consistent with formation from an evolved eucritic magma. Silica crystallizes from Sioux County melt only after $\sim 70\%$ crystallization (STOLPER, 1977). In contrast, Nuevo Laredo maybe a residual liquid after only about 40% fractional crystallization.

The low Cr_2O_3 content of Y-791195 (0.308 wt%) also indicates that this cumulate eucrite originated from an evolved parent melt. Chromium is a highly compatible element in pigeonite (*e.g.*, STOLPER, 1977) and crystallization of pigeonite-plagioclase cumulates will deplete the parent melt in Cr_2O_3 . Primitive basaltic eucrites contain $\sim 0.32\text{ wt}\%$ Cr_2O_3 ; slightly *more* than in Y-791195. Pigeonite-plagioclase cumulates from primitive basaltic eucrites will contain about 0.6 wt% Cr_2O_3 , or more if spinel is a cumulus phase. The evolved eucrite Nuevo Laredo contains 0.26 wt% Cr_2O_3 , and a pigeonite-plagioclase cumulate from this eucrite would contain about 0.5 wt% Cr_2O_3 , considerably more than in Y-791195. Hence, the Cr_2O_3 content of Y-791195 suggests that its parent melt was more evolved than any known Nuevo Laredo trend eucrite, in accord with the inferences made from FeO and Sc. For comparison, Serra de Magé and Moore County, which crystallized from evolved eucritic basalts (STOLPER, 1977), contain 0.44–0.45 wt% Cr_2O_3 .

4.3. Eucrites

Eucrite Y-82066 is similar in mineral and bulk composition to main-group eucrites, particularly Sioux County. Many elements in Y-82066 are within analytical error of mean Sioux County (Fig. 6). Note that individual samples of eucrites can vary considerably in composition, as indicated by the envelope of analyses for individual samples of Sioux County in Fig. 6. Only our Hf datum falls entirely outside the envelope of Sioux County analyses. Many of the more trace element-poor samples of the main-group eucrites, such as Juvinas and Haraiya, would also fit well within the Sioux County envelope, and we cannot claim that Y-82066 is uniquely similar to Sioux County. However, in bulk composition, Y-82066 appears to be a main-group eucrite. Its relatively high mg# and low trace element contents show that it is a primitive, main-group eucrite like Sioux County.

As mentioned above, Y-793164 is a more unusual eucrite. This eucrite is more FeO-rich than main-group eucrites, but less ferroan than Lakangaon or Nuevo Laredo. Similarly, Y-793164 is intermediate between the main-group and Lakangaon and Nuevo Laredo in Cr, Sc and REE (Fig. 6). This suggests that Y-793164 is an intermediate member of the Nuevo Laredo trend eucrites, and fills an important gap in the eucrite sample suite.

The basaltic eucrites can be divided into three groups on a plot of Sc vs. La (Fig. 8); the Stannern trend with high La and moderate Sc, the main-group with low to moderate La and Sc and the Nuevo Laredo trend with moderate La and high Sc. Scandium is a slightly incompatible element in pyroxene (PASLICK *et al.*, 1990), while La is incompatible in pyroxene (MCKAY *et al.*, 1986) and plagioclase (WEILL and MCKAY, 1975). During fractional crystallization of cumulate eucrites, both Sc and La will increase in the melt as crystallization proceeds. A model fractional crystallization curve appropriate for eucrite petrogenesis is shown in Fig. 8. This

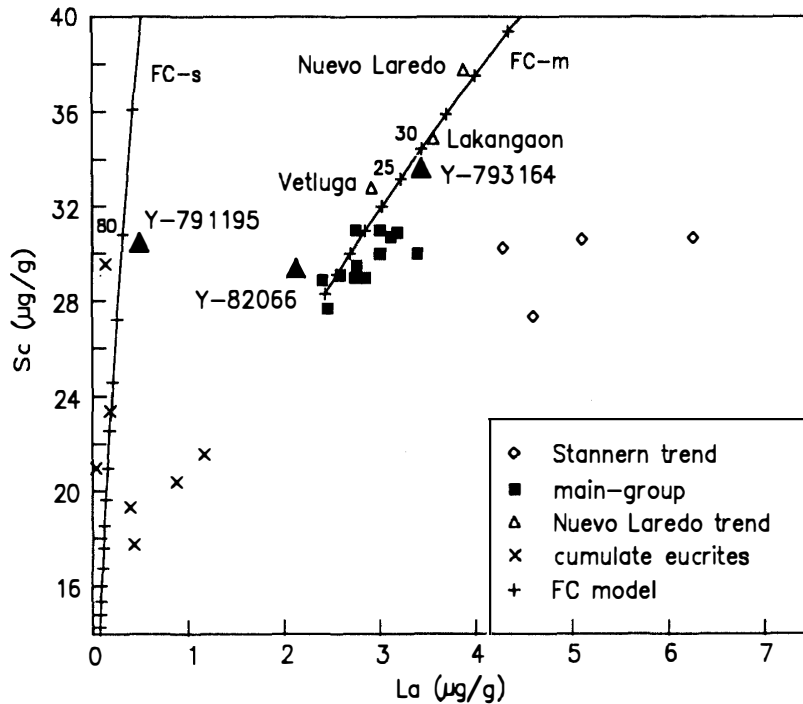


Fig. 8. *Sc vs. La* for eucrites showing Y-791195, Y-82066 and Y-793164 and mean eucrite data. Model fractional crystallization curves for pigeonite-plagioclase cumulates (FC-s) and residual liquid (FC-m) are shown. The numbers on the curves represent the percent crystallization that has occurred at that point on the curve (see text).

model was derived using the fractional crystallization equations for liquid and solid compositions of GAST (1968; eqs. (1) and (2)). We assumed that only pyroxene and plagioclase were crystallizing in a ratio of 59/41, as suggested by the pyroxene/plagioclase ratio of the eucrite peritectic (STOLPER, 1977).

On a *Sc vs. La* diagram for eucrites (Fig. 8), Y-793164 is intermediate between main-group eucrites and Lakangaon and Nuevo Laredo, and plots closest to Lakangaon. Vetluga is also a possible member of the Nuevo Laredo trend eucrites (LINDSTROM and MITTFEHLDT, 1992), and Y-793164 is intermediate in trace element composition between Vetluga and Lakangaon. Y-793164 is, therefore, an evolved melt from the HED parent body. Without knowing the composition of the parent partial melt for Y-793164 we cannot determine the amount of fractional crystallization required to generate its evolved composition. However, assuming a parent similar to Sioux County, about 25–30% crystallization of the parent as a pigeonite-plagioclase cumulate would be sufficient to generate the trace element content of Y-793164 (Fig. 8). Y-82066 plots with the more trace element-poor main-group eucrites and may be a primary partial melt.

Based on noble gas contents and exposure and terrestrial residence ages, MIURA *et al.* (1993) have suggested that Y-793164 is paired with polymict eucrite Y-792769. Y-792769 does include ferroan pyroxenes (TAKEDA, 1991) similar to those in Y-793164, and Y-793164 contains some magnesian pyroxenes similar to those in Y-792769 (YANAI and KOJIMA, 1987). Y-793164 has a fine-grained, sintered matrix texture as

does Y-792769 (TAKEDA, 1991). Petrologically, then, these two meteorites appear to be very similar. Our EMPA and INAA data on Y-793164 show no evidence for a diagenitic or magnesian eucritic component, and we did not encounter any of the magnesian pyroxenes in our sample. Therefore, our sample of Y-793164 appears to be a breccia derived from an evolved eucritic basalt intermediate between main-group eucrites and Lakangaon, as discussed above. Nevertheless, Y-793164 and Y-792769 are petrologically similar, and detailed comparison of these two meteorites should be made.

4.4. *Polymict eucrites*

Polymict breccias on the HED parent body form a continuum in compositions between the monomict eucrites and the monomict diogenites and include, in order of increasing diagenitic component, polymict eucrites, howardites and polymict diogenites (DELANEY *et al.* 1983). Eucrites are rich in Na, Al, P, Ca, Ti and incompatible trace elements, while diogenites are rich in Mg and Cr. Calcium and Eu are sensitive indicators of the amount of eucritic material in polymict breccias because Ca is about 8 times and Eu about 50 times more abundant in basaltic eucrites than in diogenites (Fig. 7). The two polymict eucrite samples, Y-791192 and Y-82049, plot in the howardite field on Fig. 7 and outside the envelope of polymict eucrites. This indicates that the samples we obtained contain substantially more than 10% diagenitic component. Comparing the Ca and Eu concentrations of Y-791192 and Y-82049 with those of average basaltic eucrites and diogenites, we calculate that Y-791192 contains between 33–40% diagenitic material, while Y-82049 contains between 46–50%*. Hence, based on the samples we received, Y-791192 and Y-82049 should be classified as howardites rather than polymict eucrites. However, polymict breccias can be inhomogeneous on the scale of the 370–450 milligram samples we received, and this can lead to erroneous classification. For example, using Ca content alone, estimates of the diogenite content of the ALHA76005-type polymict eucrites based on 30 different analyses vary from 0–21%; *i.e.*, from monomict basaltic eucrite to howardite. Additional analyses of several different splits of these Yamato polymict eucrites are required before they can be firmly classified. Our analysis of Y-791192 agrees well with an analysis of a larger split by JAROSEWICH (1990), which also suggests that this breccia contains about 30% diagenitic material and is a howardite.

Our pyroxene analyses for Y-791192 (Table 1; Fig. 1) indicate that almost all of the large pyroxene clasts in Y-791192 are similar in major element composition to Type B diogenite pyroxenes. This suggests that a major portion of the diagenitic component in Y-791192 may be derived from cumulates similar to Y-75032. Because Type B diogenites are richer in both Ca and Eu than typical diogenites, Y-791192 could be a mixture of 41–45% Type B diogenite with an average basaltic eucrite. The most magnesian pyroxenes in Y-82049 are similar to the Type A diogenites (Table 1; Fig. 1). Y-82049 also contains pyroxenes intermediate in composition between Type A diogenites and basaltic eucrites. These could be either from an unequilibrated basaltic

* In our abstract (MITTLEFEHLDT and LINDSTROM, 1992) we mistakenly reported the percentage of basaltic eucrite component, rather than the percent diogenite component as stated.

euclite like Pasamonte or clasts in Y-75011 (TAKEDA and GRAHAM, 1991), or from cumulate euclites. If there is a substantial cumulate euclite component in Y-82049, then our estimated diogenite component may be too high because some cumulate euclites contain lower Eu and Ca than do basaltic euclites. Y-82049 may be similar to Y-791960 and Y-791962, which also contain a diogenitic component (TAKEDA, 1991).

5. Conclusions

(1) The Type A diogenites are relatively uniform in composition, with only small differences in the minor phases chromite, metal and troilite. Calculations suggest that the Type A diogenites contain between about 0.6 to 1.7% trapped interstitial melt. The relationship between Type A diogenites and basaltic euclites is difficult to quantify, but the former must have formed from higher degree partial melts than the latter.

(2) The Type B diogenites are enriched in the most incompatible elements compared to a model pigeonite-plagioclase adcumulate, indicating that they contain substantial, perhaps 15%, trapped liquid component in agreement with petrologic observations. The petrology of Type B diogenites suggests that they were formed from melts that are slightly higher degree partial melts from the HED parent body than are basaltic euclites.

(3) Y-791195 is a cumulate euclite intermediate between Serra de Magé and Moore County in bulk incompatible element contents, but is more ferroan than either of these. It could have formed from a basaltic euclite similar to Sioux County after about 80% crystallization.

(4) Euclite Y-82066 is a main-group euclite similar in composition to Sioux County, and is likely a primary partial melt.

(5) Based on our sample, Y-793164 is an intermediate member of the Nuevo Laredo trend euclites, and hence represents an evolved melt from the HED parent body. Approximately 25–30% crystallization of a Sioux County-like primitive melt could yield an evolved melt with the trace element characteristics of Y-793164. Similarity between Y-793164 and polymict euclite Y-792769 suggests that they may be paired, but our data do not show that Y-793164 is polymict.

(6) The polymict euclites Y-791192 and Y-82049 contain a large fraction of diogenitic material, and, if our samples are representative, should be classified as howardites. The diogenitic component in Y-791192 appears to be similar to Type B diogenites, while that of Y-82049 is the more common Type A diogenite.

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