

The Antarctic achondrite ALHA 76005: a polymict eucrite

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Abstract—ALHA 76005 is a basaltic achondrite containing few, if any, orthopyroxenes. Its bulk major and trace element composition is like that of a non-cumulate eucrite, and unlike that of a howardite. It contains a variety of igneous clasts which differ in their textures, pyroxene/plagioclase ratios and pyroxene and plagioclase compositions. One clast, No. 4, was found to have the REE pattern of a cumulate eucrite and an oxygen isotopic composition different from that of the bulk meteorite. Both the chemical and oxygen isotopic composition of clast No. 4 suggest that it was derived from a source different from its host. These observations lead to the conclusion that ALHA 76005 is a polymict eucrite.

INTRODUCTION

DIFFERENT criteria have been used to assign pyroxene-plagioclase achondrites to their eucrite and howardite sub-groups. PRIOR (1920) called those in which pigeonite is the dominant pyroxene 'eucrites' and those in which hypersthene is the dominant pyroxene 'howardites'. MASON (1962) showed that the eucrites and howardites so defined plot in different fields on a graph of their total CaO contents vs their molecular FeO/FeO + MgO ratios, a modified version of which is reproduced here as Fig. 1. DUKE and SILVER (1967), however, preferred a structural classification in which eucrites are defined as monomict breccias rich in clinopyroxene and howardites as polymict breccias rich in both clinopyroxene and orthopyroxene. STOLPER (1977) used a modified version of that scheme when he referred to eucrites as achondrites which are unbrecciated or monomict breccias consisting principally of plagioclase and pigeonite. MASON *et al.* (1979) pointed out that three polymict achondrites, Macibini, Bialystok and Nobleborough, have dominant pigeonite. They also noted that Binda, which has dominant orthopyroxene, is monomict, but a careful search by GARCIA and PRINZ (1978) revealed rare, tiny xenolithic clasts that indicate that Binda is actually polymict.

The situation is best summarized in Fig. 1. We have plotted chemical data for all of the achondrites in the review of MASON *et al.* (1979), except for Shergotty which was omitted because of its unique mineralogy and ALHA 76005 for which we have substituted data from this work, plus data for Yamato 7308 from YAGI

et al. (1978), Yamato 74159 from TAKEDA *et al.* (1978) and clast No. 4 from this work. For each meteorite except Binda, the same reference was used for the mineralogical and structural information given in Fig. 1 as for the chemical data. For diogenites, chemical data were taken from MASON (1963), except for those meteorites for which more recent data are given by McCARTHY *et al.* (1972). It is seen that all meteorites in which pigeonite is the dominant pyroxene fall

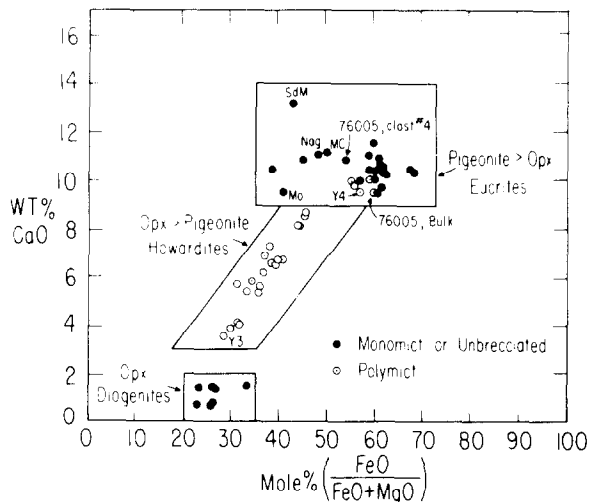


Fig. 1. Pyroxene-plagioclase achondrites in which pigeonite is the dominant pyroxene (eucrites) have a different range of chemical composition from those in which orthopyroxene predominates (howardites). Polymict individuals are found in both groups. According to this definition, both ALHA 76005 and clast No. 4 from it are eucrites. Where eucrite and howardite data are from literature sources other than MASON *et al.* (1979), individual meteorites are labelled: Y3—Yamato 7308, Y4—Yamato 74159. Also labelled are eucrites known to have cumulus textures: SdM—Serra de Magé, MC—Moore County, Nag—Nagaria, Mo—Moama.

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within a restricted composition range on Fig. 1, with CaO > 9% and FeO/FeO + MgO between 0.35 and 0.70. These we call eucrites. Five of those plotted are known to be polymict, including the one which is the subject of this paper, but it is possible that detailed studies in the future will reveal that many more are polymict. Except for the diogenites, those meteorites in which orthopyroxene predominates over clinopyroxene fall in a linear array in Fig. 1, from 3.5% CaO and FeO/FeO + MgO of 0.29 to 8.7% CaO and FeO/FeO + MgO of 0.46. These we call howardites. All of these are polymict.

It is clear that incorporation of the terms monomict and polymict into the definitions of eucrites and howardites either leads to unclassified achondrites or groups achondrites together which have different mineralogical and chemical compositions. We believe that the best classification scheme is that suggested by MASON (1962) who was the first to show that the mineralogical classification adopted by PRIOR (1920) is equivalent to the chemical one shown here in Fig. 1.

The purpose of the present paper is to show an example of an achondrite, ALHA 76005, whose mineralogical, major element, trace element and oxygen isotopic compositions are those of eucrites, but which is polymict on the basis of petrography, chemistry and oxygen isotopic compositions. It was OLSEN *et al.* (1978) who first pointed out that this meteorite, though polymict, has the chemistry of a eucrite. MIYAMOTO *et al.* (1979a) coined the phrase 'polymict eucrites' to describe such meteorites and included ALHA 76005 among them.

EXPERIMENTAL TECHNIQUES

Sampling

The bulk sample of ALHA 76005 was removed from an edge joining two saw-cut flat surfaces of the meteorite. After removal of the exterior surface to avoid contamination, a sample was taken by scraping a stainless steel dental tool along the edge for a distance of about 20 mm and to a depth of about 5 mm. Since the sample dimensions greatly exceed the grain size of the meteorite, we believe the bulk sample to be a representative one.

The attention of the authors was attracted to a large, 10 × 14 mm, coarse-grained clast (No. 4) on a cut surface of the meteorite. The surface of the clast was scraped off with a dental tool and discarded to avoid contamination. The interior of the clast was then excavated, leaving about 2 mm around the edges. The clast was dug to a depth of up to 3 mm. This sample was then split into two portions, one for INAA and the other for oxygen isotopic analysis (CLAYTON *et al.*, 1979). Again, sample dimensions greatly exceed the grain size, so that the clast sample is believed to be homogeneous and representative. A polished thin section was then prepared from the portion of the clast below the hole from which material had been sampled.

Electron microprobe

All analyses were obtained with an ARL-EMX-SM automated electron microprobe, equipped with a Nuclear Semiconductor AUTOTRACE energy-dispersive X-ray analyser and an on-line NOVA 2/10 computer. Operating conditions for energy-dispersive analyses were 15 keV accelerating voltage, 0.1 μ A beam current and a beam spot diam-

eter of approximately 3 μ m. Analyses of pyroxene grains in the matrix of the bulk meteorite were obtained using a beam diameter of approximately 25 μ m because the pyroxenes generally contain exsolution lamellae and an average composition was desired. Sodium analyses of feldspars in clast No. 4 were obtained using wavelength dispersion. Operating conditions were 15 keV accelerating voltage and 1.0 μ A beam current. The beam was defocused slightly and rastered over a small area within the feldspar grains during each 30 sec analysis in order to minimize vaporization of sodium.

For both analysis techniques, a set of well-characterized natural and synthetic minerals and glasses were used as standards. During each analytical session, some standards were analysed as unknowns in order to monitor instrument drift.

Neutron activation

The bulk sample of ALHA 76005 was analysed for Na, Mg, Al, K, Ca, Ti, V, Mn and Dy in the same series of irradiations as the bulk sample of CG-11 in DAVIS *et al.* (1978). Sample preparation, irradiation and counting conditions, standards and procedures for flux corrections were thus exactly those reported in that paper. The sample was then removed from its polyethylene vial, reweighed and sealed in a Suprasil vial which was then washed with HNO₃. Then the vial was wrapped in aluminum foil and irradiated with other meteorite samples, SP which is the 'Standard Pottery' of PERLMAN and ASARO (1969), BCR-1, several chemical standards described in GROSSMAN and GANAPATHY (1976) and an empty Suprasil vial for blank correction for 24 hr at a flux of 1.1×10^{14} neutrons $\text{cm}^{-2} \text{sec}^{-1}$ in the graphite reflector, first row, of the University of Missouri Research Reactor (MURR). After two days of cooling, the vials were washed in aqua regia and counted three times at the University of Chicago: first, for approximately 2 hr; second, until the highest peak reached 10⁶ counts; and third, until the highest part of the background reached 5×10^5 counts.

Variation in neutron fluence within the irradiation can be corrected for by determining the specific activities of ⁵⁹Fe (for thermal neutrons) and ⁵⁴Mn (for fast neutrons) produced from minor amounts of iron in the aluminum foil in which each sample and standard vial was wrapped. After the irradiation, foils were removed from the vials, pressed into 5 mm diameter × 2 mm thick pellets, weighed, mounted on aluminum cards and counted on a Ge-Li detector about one month later. Within the irradiation can, fast and thermal neutron fluences are strongly positively correlated, with the fluence of fast neutrons varying somewhat less than that of thermal neutrons. These flux corrections depend on the assumption that the aluminum foil is homogeneous in Fe content on a 500 cm^2 scale, the amount normally used in each irradiation. We have evidence from another irradiation that this assumption is justified. In it, two Au standards were placed in the irradiation can fairly far apart. Counting of their foils indicated a neutron fluence difference of 11.9%. Using one Au standard as a standard and applying the flux correction from the foils, we calculated the Au content of the other standard to be within 0.3% of the amount actually present. Also in that irradiation, SP and BCR-1 had a thermal neutron fluence difference of 14.2%; yet, when the flux correction was applied, excellent agreement was obtained between these two standards for specific activities of all elements whose counting statistics were good.

Clast No. 4 and aliquants of SP, BCR-1 and Johnson-Matthey Specpure MgO, Al₂O₃, SiO₂, CaCO₃ and TiO₂ were sealed in individual high-density polyethylene vials and individually irradiated in the second row of the graphite reflector of the MURR via a pneumatic rabbit for 5 min at a flux of 4×10^{13} neutrons $\text{cm}^{-2} \text{sec}^{-1}$. After a decay period of five minutes, each vial was counted for 100 sec for

^{28}Al and, after a total of 10 min of decay, each was counted for 500 sec for ^{27}Mg , ^{49}Ca , ^{51}Ti and ^{52}V using a Ge-Li detector. After six to seven hours, each vial was counted for 1000 sec for ^{24}Na , ^{56}Mn and ^{165}Dy . Variations in neutron flux throughout the run were monitored by periodically irradiating aluminum wires doped with Au and counting ^{198}Au several days later. No significant variations were found. An empty vial was also irradiated and counted for blank corrections. No corrections were significant. In addition to being used as standards, the Speccure compounds were also used to correct for interferences due to the following fast neutron reactions: $^{24}\text{Mg}(n, p)^{24}\text{Na}$; $^{27}\text{Al}(n, \alpha)^{24}\text{Na}$; $^{27}\text{Al}(n, p)^{27}\text{Mg}$ and $^{28}\text{Si}(n, p)^{28}\text{Al}$. The clast was then transferred to a Suprasil vial and irradiated, along with aliquants of SP and BCR-1, several chemical standards described by GROSSMAN and GANAPATHY (1976) and a chemical standard containing all 14 REE in approximately chondritic proportion to one another, for six days at a flux of 3×10^{13} neutrons $\text{cm}^{-2} \text{sec}^{-1}$ in the Vertical Thimble, Position 25, of the CP-5 reactor at Argonne National Laboratory. The ensuing procedures for counting and data reduction were described in detail in GROSSMAN and GANAPATHY (1976) and for flux correction as above for the bulk sample. During transfer of the clast from the polyethylene to the silica vial, about 50% of the sample was lost and the remainder was reweighed prior to the final irradiation. For the bulk meteorite, sample loss amounted to only $\sim 3.5\%$, and will be ignored in the remainder of this paper.

PETROGRAPHY AND MINERAL CHEMISTRY RESULTS

The original description of ALHA 76005 was given by OLSEN *et al.* (1978). Further details of pyroxene and plagioclase compositions were presented by MIYAMOTO *et al.* (1979b). ALHA 76005 is an achondrite consisting of several different types of clasts contained in a matrix of comminuted pyroxene and plagioclase. Several of these are described below.

Clast No. 1

This clast, 1.4×0.7 mm, consists of plagioclase laths ($10\text{--}30 \mu\text{m}$ wide and $100\text{--}200 \mu\text{m}$ long) with pyroxene in a subophitic to ophitic texture (Fig. 2). The plagioclases range from An_{81} to An_{91} (Fig. 3) and the pyroxenes from pigeonite to sub-calcic augite (Fig. 4). Abundant submicron-sized exsolution lamellae were seen in the pyroxenes. The pyroxene/plagioclase ratio is $\sim 1:1$ by weight.

Clasts Nos 2 and 3

Clasts Nos 2 and 3

These contain plagioclase crystals that are either stubbier (clast No. 2) or shorter (clast No. 3) than those of clast No. 1. Those in clast No. 2 are nearly uniform in length, $\sim 140 \mu\text{m}$, and $30\text{--}60 \mu\text{m}$ in width. In clast No. 3, they are $10\text{--}40 \mu\text{m}$ wide and $70\text{--}100 \mu\text{m}$ long. In both clasts, the plagioclase is intergrown with pyroxene in an intergranular to subophitic texture and some plagioclase exhibits undulose extinction. Plagioclases range from An_{83} to An_{92} (Fig. 3) and pyroxenes from pigeonite to sub-calcic augite (Fig. 4) in both clasts. Exsolution lamellae in the pyroxenes are $<1 \mu\text{m}$ wide, closely-spaced, rare in most grains but very abundant in some. Clast No. 2, shown in Fig. 5, is 1.0×0.7 mm and has a pyroxene/plagioclase ratio of $\sim 2:1$. Clast No. 3, 1.0×0.8 mm, has a pyroxene/plagioclase ratio of $\sim 3:1$. Clasts 2 and 3 are thus different in texture and mineralogy from clast No. 1.

Clast No. 4

This clast, 8×14 mm, consists of plagioclase laths up to $200 \mu\text{m}$ wide and $2000 \mu\text{m}$ long with pyroxene in a subophitic to ophitic texture (Fig. 6). Interstitial to these phases are patches comprising up to 10% of the entire clast which are composed of a very fine-grained mixture of pyroxene, a nickel-free iron sulfide and a silica mineral. Accessory ilmenite, containing 1% MgO and 1% Al_2O_3 , was also found. The plagioclases range from An_{80} to An_{91} (Fig. 3). The pyroxenes extend to more calcic compositions than in the previous three clasts (Fig. 4) and contain $\sim 1.5\%$ Al_2O_3 on average. Exsolution lamellae, $1\text{--}2 \mu\text{m}$ thick,

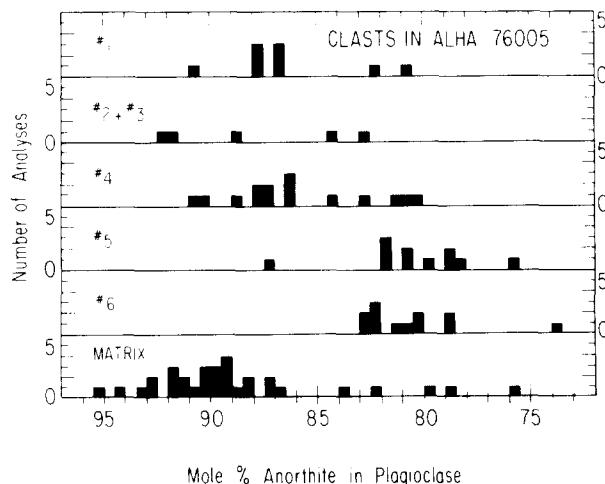


Fig. 3. Plagioclase compositions in clasts and matrix grains in ALHA 76005.

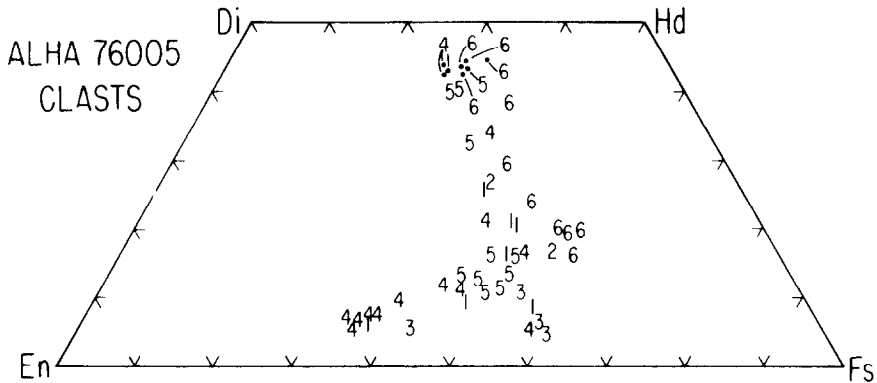


Fig. 4. Point analyses of pyroxenes in clasts in ALHA 76005. Symbols are clast numbers referred to in the text.

are present in some grains and are unevenly distributed within their hosts. This clast is approximately 45% pyroxene and 45% plagioclase, and is the one whose trace element composition is studied here and whose oxygen isotopic composition was studied by CLAYTON *et al.* (1979). The grain size, pyroxene/plagioclase ratio and pyroxene compositions in this clast distinguish it from the previous three.

Clast No. 5

This clast, 1.4×1.1 mm, consists of plagioclase laths ($100 \mu\text{m}$ wide and as much as $900 \mu\text{m}$ long), skeletal plagioclase and pyroxene in a subophitic to ophitic texture, and minor ilmenite, iron sulfide and a silica-rich phase, possibly glass, often intergrown with plagioclase. The pyroxene/plagioclase ratio is $\sim 1:2$. The plagioclases tend to be more albitic than in the previous four clasts, ranging from An_{76} to An_{87} (Fig. 3). The pyroxenes (Fig. 4), like those in clast No. 4, extend to more calcic compositions than in clasts 1–3, but tend to be less magnesian than those in clast No. 4. They contain exsolution lamellae $< 1 \mu\text{m}$ in size. The skeletal habit of some of the plagioclase, the phase compositions and the pyroxene/plagioclase ratio set this clast apart from the first four.

Clast No. 6

This clast, 1.5×2.6 mm, consists predominantly of plagioclase and pyroxene and may have a cumulate texture (Fig. 7). Plagioclase laths are as large as in clast No. 5. Two laths of a silica polymorph, 1 mm in length, one of ilmenite, $750 \mu\text{m}$ in longest dimension, and accessory troilite are also present. Plagioclase ranges from An_{74} to An_{83} (Fig. 3) and pyroxene from sub-calcic augite to augite (Fig. 4). All pyroxene grains contain abundant, submicron exsolution lamellae. The clast is approximately 60% plagioclase, 30% pyroxene and 10% other phases. Most pyroxenes in this clast are much more FeO-rich than those in clast No. 5.

Poikilitic plagioclase–pyroxene clasts

OLSEN *et al.* (1978) described pyroxene crystals that are poikilitically enclosed by plagioclase. The pyr-

oxenes are abundant, remarkably uniform in size, $8\text{--}10 \mu\text{m}$, and are regularly spaced throughout the interiors of the plagioclases. No objects of this kind were observed in any of the above clasts. In the four samples studied in this work, the host plagioclase grains range from An_{88} to An_{93} . The small sizes of the pyroxenes makes microprobe analyses of them difficult due to contamination by surrounding plagioclase and it is likely that the high Al_2O_3 contents reported by Olsen *et al.* are in error. Molar $\text{FeO}/\text{FeO} + \text{MgO}$ ratios in pyroxene range from 0.57 to 0.63 and some contain $< 5\%$ CaO.

Grains in matrix

The matrix of ALHA 76005 consists entirely of comminuted grains of pyroxene, plagioclase and glass, with minor oxide phases (OLSEN *et al.*, 1978; MIYAMOTO *et al.*, 1979b). Broad-beam microprobe analyses of the pyroxenes are shown in Fig. 8. Their compositions are in good agreement with those in the clasts, except that many pyroxenes in clast No. 4 are more magnesian than any seen in the matrix and that pyroxenes in several clasts were found to be more calcic than any in the matrix. The latter discrepancy may be due to the fact that extreme CaO contents of exsolution lamellae make a major contribution to some point analyses in the clasts, but tend to be averaged out in the broad-beam analyses performed on matrix grains. The former discrepancy, however, suggests that objects like clast No. 4 contributed relatively little material to the population of matrix grains. Pyroxenes in both matrix and clasts are pigeonite to sub-calcic augite. The absence of hypersthene suggests that ALHA 76005 is a eucrite (PRIOR, 1920; DUKE and SILVER, 1967). Most matrix pyroxenes contain very fine ($\ll 1 \mu\text{m}$), closely-spaced exsolution lamellae which are relatively uniformly distributed within their hosts. Some of the larger pyroxene grains contain an additional set of coarser, $1\text{--}2 \mu\text{m}$ thick, evenly-spaced ($10\text{--}30 \mu\text{m}$ apart), irregularly-distributed exsolution lamellae that intersect the finer set at an angle of $\sim 7^\circ$. Such grains with complex exsolution were seen in none of the clasts studied here.

Plagioclase compositions (Fig. 3) range from An_{76}



Fig. 2. ALHA 76005, Clast No. 1. Ophitic pyroxenes (Px) enclosing elongate laths of plagioclase (Pl), with scattered pools of dark mesostasis (Ms).



Fig. 5. ALHA 76005, Clast No. 2. Stubby plagioclase laths (light grey, Pl) with intergranular pyroxenes (dark grey, Px).

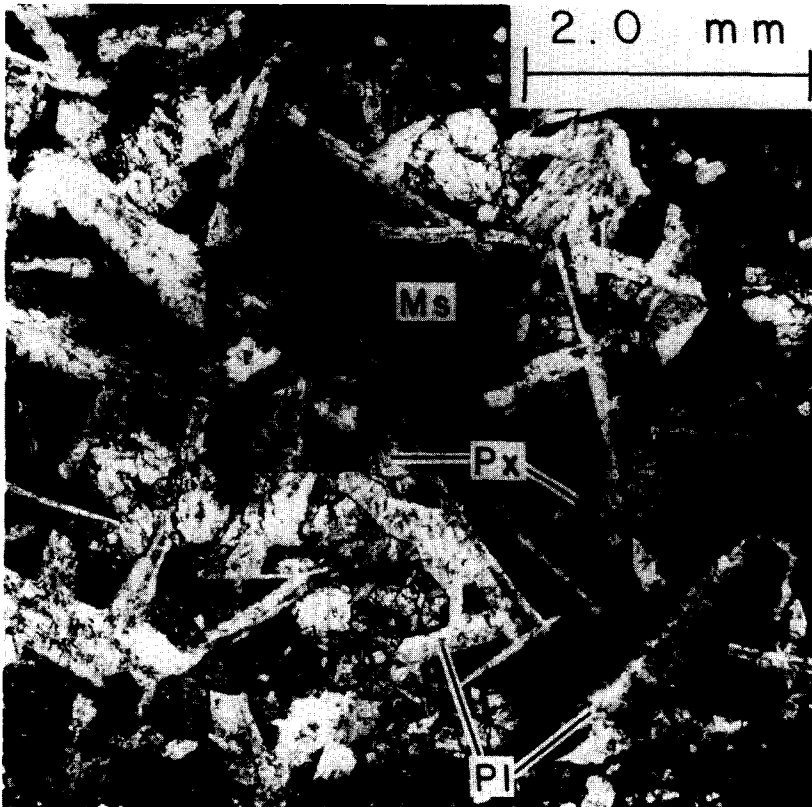


Fig. 6. ALHA 76005, Clast No. 4. Long, narrow plagioclase laths (white, Pl) and subophitic pyroxenes (grey, Px) with large pools of dark mesostasis (Ms).



Fig. 7. ALHA 76005, Clast No. 6. Large, mostly euhedral plagioclase laths (white, Pl) and lesser tridymites (Tr, long white crystal), form a cumulate meshwork, the interstices of which are filled with anhedral pyroxenes (dark grey, Px), ilmenites (not visible in photo), and pools of dark mesostasis (Ms).

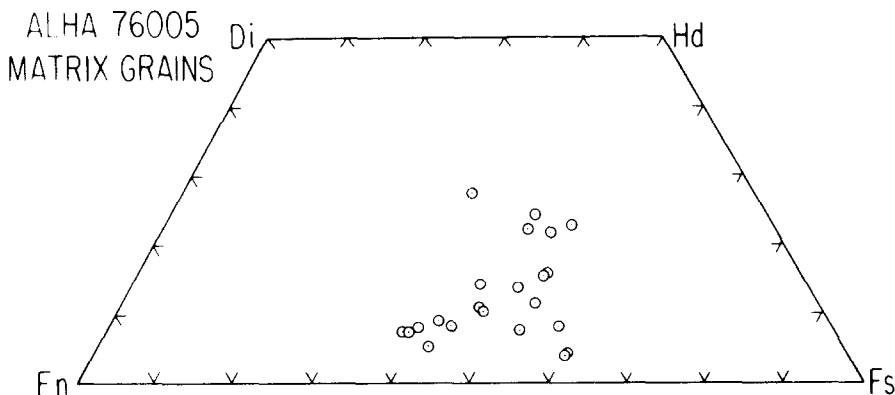


Fig. 8. Broad-beam electron microprobe analyses of individual pyroxene grains in the matrix of ALHA 76005. Very few orthopyroxenes are present, indicating that the achondrite is a eucrite.

to An_{96} , with the majority of grains in the range An_{87} to An_{92} , in good agreement with the histogram presented by MIYAMOTO *et al.* (1979b). The most anorthite-rich compositions seen in the matrix are more calcic than any plagioclases observed in the clasts. The matrix may thus contain fragments from rock types that were not studied as clasts.

In summary, petrographic and mineral-chemical data indicate the presence of several different types of clasts with different origins. Furthermore, there is evidence from the grains in the matrix that rock types which were not found in this study have also contributed material to this meteorite. ALHA 76005 is a polymict breccia.

MAJOR AND TRACE ELEMENT RESULTS

Major element composition

Analytical data for the bulk meteorite are presented in Table 1, in which all iron is assumed to be present as FeO and SiO_2 is determined by difference. Good agreement exists between these data and INAA determinations of several major elements in the same meteorite by MITTFEHLDT (1979). There is also excellent agreement between the data in Table 1 and wet chemical analyses by MIYAMOTO *et al.* (1979b) and by Jarosewich given in OLSEN *et al.* (1978) for all oxides except FeO. Our value for that element is 13% higher than that reported by Olsen *et al.*, but only 5% higher than that of Miyamoto *et al.* The agreement for SiO_2 is fortuitous, as these workers reported 2.25% and 1.50%, respectively, of elements not determined here. The FeO/ SiO_2 ratio determined here is thus significantly higher than the ratios reported by other workers. This may be due to the heterogeneity of the meteorite and the relatively small sample size used in this work. Nevertheless, all three bulk analyses plot well within the field occupied by the eucrites in Fig. 1. Analytical data for howardites, non-cumulate eucrites and the cumulate eucrites Moama, Serra de Magé and Moore County from the literature are also listed in Table 1. Howardites have a different range of concentrations from non-cumulate eucrites

for most major and minor elements. For each of these elements, ALHA 76005 either falls within the eucrite range or much closer to it than to the howardite range. Furthermore, on the basis of its TiO_2 , Al_2O_3 and FeO contents, the bulk meteorite appears to be a non-cumulate, rather than a cumulate, eucrite.

Analytical data for clast No. 4 are also shown in Table 1. Of the major elements, titanium, aluminum, magnesium, calcium and sodium were determined in the first irradiation, prior to sample loss. A modal analysis can be calculated from these data, if assumptions based upon information from our petrographic and electron microprobe study are made. Assuming that 0.5% troilite and some tridymite are present, that all TiO_2 , Na_2O and MgO are present as ilmenite, plagioclase and pyroxene, respectively, that the average pyroxene composition is $Wo_{15}En_{40}Fs_{45}$ with 1.5% Al_2O_3 (compared to the average of $Wo_{20}En_{41}Fs_{39}$ with the same Al_2O_3 content from microprobe analyses) and that the average plagioclase composition is An_{83} (compared to An_{86} from the microprobe), the mode becomes 38.0 wt% plagioclase, 55.5% pyroxene, 1.25% ilmenite, 0.5% troilite and 4.75% tridymite, giving 50.8% SiO_2 and 15.7% FeO for the elements not determined in this experiment. For each of the major and minor elements whose abundances distinguish howardites from non-cumulate eucrites, clast No. 4 falls within the concentration range for the latter or closer to it than to that for howardites. It also plots in the eucrite field in Fig. 1. Unambiguous assignment of it to either the cumulate or non-cumulate class of eucrites cannot be made on the basis of its major and minor element contents. The clast and its host do appear to be different in composition, however, particularly for Al_2O_3 , CaO, Na_2O and MnO.

In transferring the sample of the clast into a silica tube prior to the second irradiation, about 50% of the sample was lost. Of the major elements, only iron and sodium were determined in this experiment; however, making the same assumptions that were used above for the entire sample, we can re-construct the complete mineralogical composition of the remaining ali-

Table 1. Major and trace element concentrations in the bulk meteorite and clast #4. Values in ppm unless otherwise indicated.

Sample	Wt (mg)	Wt (mg)	SiO ₂ ¹ (%)	TiO ₂ (%)	Al ₂ O ₃ (%)	FeO (%)	MgO (%)	CaO (%)	Na ₂ O (%)
ALHA 76005, Bulk	45.70	44.04	48.5±.8	.55±.12	12.4±.1	20.07±.04	7.54±.59	9.47±.50	.478±.002
ALHA 76005, Clast 4	5.02	2.50	See text	.66±.08	13.9±.1	17.83±.03	7.50±.46	10.8±.4	.715±.009
Irradiation ²	R, I	L		R	R	L	R	R	R
Howardites ³				.11-.46	.71-8.7	15.1-21.2	11.7-22.3	11.1-6.7	.030-.284
Non-Cumulate Eucrites ⁵				.54-.96	11.9-13.0	17.7-19.3	5.5-7.0	10.2-10.5	.42-.57
Cumulate Eucrites	Moama ⁶ Serra de Magé ^{7,8} Moore County ^{7,8}			.22	13.7	14.9	11.9	9.5	.22
				.11	20.9	10.0	7.52	11.1	.30
				.32	15.6	15.0	8.4	11.1	.45
Sample	Sr	Ba	La	Ce	Nd	Sm	Eu	Tb	
ALHA 76005, Bulk	82±11	35±12	3.87±.02	8.95±.12	9.1±1.4	2.372±.004	.698±.005	.632±.018	
ALHA 76005, Clast 4	75±15	<60	1.24±.01	3.24±.09	<5.1	.898±.004	.457±.017	.236±.024	
Irradiation	L	L	L	L	L	L	L	L	
Howardites	25-49	1.8-17.7	.59-1.89	1.74-5.1	.87-3.3	.51-1.11	.0126-.400	.13-.28	
Non-Cumulate Eucrites	50-89	27-58	1.94-5.15	6.50-9.1 ⁴	5.3 ⁴	1.30-3.35	.50-.83	.40-.52 ⁴	
Cumulate Eucrites	Moama Serra de Magé Moore County		.206	.508	.407	.159	.410		
		55 ⁴	7.59		1.22	1.06	.377	.298	
			22.5		3.08	2.81	.938	.591	

¹Determined by taking the difference between 100% and the sum of the concentrations of all other oxides.

²The bulk meteorite and the clast were irradiated separately. Each was subjected to a 'rabbit' irradiation, R, and a long irradiation, L. The bulk meteorite also had an intermediate irradiation, I.

³Data of Fukuoka *et al.* (1977), except where otherwise noted.

⁴Data of Palme *et al.* (1978), except that Serra de Magé was omitted from the eucrite data.

⁵From compilation of Fukuoka *et al.* (1977), except where otherwise noted.

⁶Major elements from Lovering (1975); trace elements from Hamet *et al.* (1978).

⁷Major elements from compilation of Mason *et al.* (1979).

⁸Ba and REE data of Schmetzler and Philpotts (1969), except where otherwise noted.

quant. The resulting mode is 35.5% plagioclase, 61.9% pyroxene, 0.8% tridymite and 0.5% troilite, if the same amount of ilmenite is assumed to be present as there was initially. Sample loss apparently occurred in such a way that the pyroxene/plagioclase ratio increased by ~20%. For the elements not determined in this irradiation, this mode implies concentrations of 48.9% SiO₂, 13.0% Al₂O₃, 8.4% MgO, 10.5% CaO and 0.7% TiO₂.

Trace element composition

Trace element data for the bulk meteorite and clast No. 4 are also given in Table 1, along with literature data for howardites and eucrites. Within the limits of error, our data for the bulk meteorite agree with concentrations of those trace elements determined by MITTFELDLT (1979), except for Co, La, Sm and Tb. It is not known whether the discrepancies for the latter four elements are significant, as Mittlefehldt only quotes the mean uncertainty for each element in a group of 31 samples. For the bulk meteorite, twelve trace elements fall within the concentration ranges for non-cumulate eucrites and not within those of howardites. Three elements fall in neither range, but are

closer to the eucrite range than the howardite range. Only Ni falls in the howardite range and not in the eucrite range. The rare earth element (REE) pattern of ALHA 76005 is shown in Fig. 9 with those of other eucrites, both cumulate and non-cumulate. It is quite similar to that of the non-cumulate eucrite Nuevo Laredo and quite distinct from those of the cumulate eucrites. It is quite unlike the REE pattern reported for this meteorite by NAKAMURA *et al.* (1979) in that it does not have a 50% positive Ce anomaly and REE abundances are significantly higher than those in Juvinas. The Hf and Ta contents of ALHA 76005 are within the ranges for non-cumulate eucrites and are substantially higher than those of the cumulate Serra de Magé. Clast No. 4 is significantly different in composition from the bulk meteorite, having lower REE, Hf, Ta, W, Au and Th contents and higher Sc and Co contents than the latter. In Fig. 9, the REE pattern of clast No. 4 is distinctly different from those of the non-cumulate eucrites, but quite similar to that of the cumulate eucrite Moore County. The important differences in bulk chemical composition between clast No. 4 and the bulk meteorite underscore the fact that ALHA 76005 is a polymict eucrite. In the ensuing

Na ₂ O (%)	K ₂ O (%)	K ₂ O (%)	MnO (%)	Cr ₂ O ₃ (%)	Sc	V	Co	Ni	Br
	.0642±.0064		.554±.004	.3541±.0007	33.64±.01	68.3±5.4	6.72±.02	60±12	.286±.055
.668±.002		.0504±.0080	.401±.008	.3544±.0004	38.31±.05	71.6±4.6	17.26±.03	<440	<.18
L	L	L	R	L	L	R	L	L	L
	.0037-.0285		.434-.666	.53-1.02	19.4-26.2	90-139	11.1-26.3	15-360	
	.03-.07		.51-.56	.28-.33	27-41	86-108	2-30	5-13	
	.01		.50	.61					
			.36	.33	22.1 ⁴	111 ⁴	9.50 ⁴		
			.31	.44					
Dy	Yb	Ta	Hf	Ta	W	Au (ppb)	Th		
4.63±.70	2.26±.02	.294±.004	1.44±.02	.187±.008	.58±.17	8.95±.44	.366±.019		
2.21±.68	1.11±.03	.192±.004	.786±.014	.106±.023	<.53	2.5±1.2	.127±.020		
R	L	L	L	L	L	L	L		
.90-1.86	.63-1.15	.098-.165	.47-.63	.04-.18 ⁴	.037 ⁴	2.2-21			
2.48-2.95 ⁴	1.32-2.48	.24-.50	1.05-1.56 ⁴	.14-.22 ⁴	.063 ⁴	.4-17	.30-.58 ⁴		
.414	.388	.0647							
.554	.367		.14 ⁴	.08 ⁴					
1.62	1.08								

discussion, it is assumed that xenolithic clasts constitute a small fraction of the bulk meteorite, thus permitting discussion of its REE pattern in terms of petrogenetic models for the formation of a single, homogeneous igneous rock.

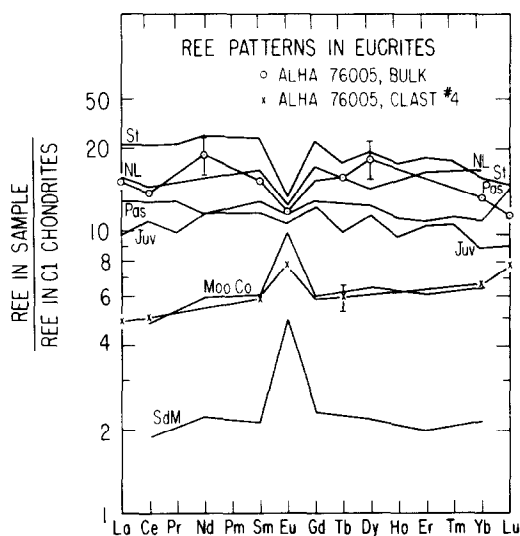


Fig. 9. ALHA 76005 has the REE pattern typical of a non-cumulate eucrite, while clast No. 4 from it has the REE pattern of a cumulate eucrite, indicating that the meteorite is polymict. Data for Stannern (St)—HASKIN *et al.* (1966), SCHNETZLER and PHILPOTTS (1969), GAST *et al.* (1970); Nuevo Laredo (NL)—GAST and HUBBARD (1970); Pasamonte (Pas)—HASKIN *et al.* (1966), GAST *et al.* (1970); Juvinas (Juv)—HASKIN *et al.* (1966), SCHNETZLER and PHILPOTTS (1969); Moore County (Moo Co) and Serra de Magé (SdM)—SCHNETZLER and PHILPOTTS (1969). When more than one reference is listed, the average is plotted.

CONSOLMAGNO and DRAKE (1977) explained eucritic REE patterns in terms of partial melting of a source region having chondritic relative and absolute REE abundances and fractional crystallization of the resulting liquids. Using liquid-crystal partition coefficients, they found that Stannern resembles the liquid produced after ~4% melting of a source region consisting of 50% olivine, 30% metal, 10% orthopyroxene, 5% clinopyroxene and 5% plagioclase. Other non-cumulate eucrites with smaller negative europium anomalies and lower REE abundances resemble liquids produced after greater amounts of partial melting, up to ~15%, which cause plagioclase to be drained from the residue. According to this model, ALHA 76005 would be interpreted as a melt produced from >4% and <10% partial melting of such a source because it has REE abundances and a Eu depletion intermediate between those of Stannern and the main non-cumulate eucrite group. As such, its plagioclase should be much more calcic than that of Stannern, An₈₀ (DUKE and SILVER, 1967). Although plagioclase grains in the matrix of this meteorite vary widely in composition, this seems to be the case as the mean composition is An₈₉.

On a plot of weight per cent Ti vs molar Fe/Fe + Mg, MITTFELDLT (1979) showed a trend of residual melts produced during equilibrium crystallization of eucritic liquids and another of increasing partial melting of the eucrite source region. The two trends converge, however, in the vicinity of the diagram where the analysis of ALHA 76005 lies and the diagram is not sufficiently sensitive to distinguish between these two modes of origin for this particular meteorite. The fused bead microprobe analysis

reported by MITTFELDLT (1979), 0.46% Ti and $\text{Fe}/\text{Fe} + \text{Mg} = 0.616$, plots on the edge of the former trend, a fact which caused Mittlefehldt to interpret the meteorite as a liquid residue produced after 10–15% crystallization. This is in conflict with our interpretation of the meteorite as a partial melt, based on its REE pattern. But OLSEN *et al.* (1978) reported a Ti content of 0.44% and an $\text{Fe}/\text{Fe} + \text{Mg}$ ratio of 0.594 and MIYAMOTO *et al.* (1979b) gave 0.47% Ti and $\text{Fe}/\text{Fe} + \text{Mg} = 0.581$. Although our Ti analysis is much more uncertain than others cited here, our $\text{Fe}/\text{Fe} + \text{Mg} = 0.599$. Data from these sources plot along the partial melting trend, rather than the differentiation trend, and suggest that ALHA 76005 represents a liquid produced by a greater degree of partial melting of the eucrite source region than that which produced Stannern. This is entirely consistent with our interpretation of the REE pattern of ALHA 76005.

Nuevo Laredo has a very similar REE pattern to ALHA 76005 and, on the basis of this alone, could be interpreted in the same way. Noting, however, that the atomic $\text{FeO}/\text{FeO} + \text{MgO}$ ratio of Nuevo Laredo is considerably higher than that of Stannern, CONSOLMAGNO and DRAKE (1977) recognized that the former could not be produced by a greater degree of partial melting of the same source as Stannern. They proposed instead that Nuevo Laredo is the crystallization product of the melt remaining after 30% fractional crystallization of plagioclase and pigeonite from a parent liquid whose composition was the same as that of the main group of non-cumulate eucrites. This interpretation is not required for ALHA 76005, however, because its atomic $\text{FeO}/\text{FeO} + \text{MgO}$ ratio is 0.60 ± 0.02 , which is slightly lower than that of Stannern, 0.62.

CONSOLMAGNO and DRAKE (1977) proposed that the cumulate eucrites crystallized after substantial amounts of fractional crystallization from a melt having the composition of the main eucrite group. The REE pattern of Serra de Magé resembles that calculated to be in the pigeonite and plagioclase solidifying after 50% fractional crystallization, while that of Moore County can be produced after 85% fractional crystallization. Accordingly, the pyroxene has a higher $\text{FeO}/\text{FeO} + \text{MgO}$ ratio and the plagioclase is more albitic in Moore County than in Serra de Magé (DUKE and SILVER, 1967). MA and SCHMITT (1979) reviewed the difficulties for this model posed by the fact that quantitative considerations of $\text{FeO}/\text{FeO} + \text{MgO}$ ratios, minor element abundances and concentrations of trace elements other than REE suggest that there is no genetic relationship between the cumulate and non-cumulate eucrites. Furthermore, MA and SCHMITT (1979) pointed out that the $\text{FeO}/\text{FeO} + \text{MgO}$ ratio of Moore County pyroxene is far less than what it should be, 0.88, if it formed from the same parent liquid as Serra de Magé after the additional degree of fractional crystallization indicated by the REE patterns. They concluded that these two cumulate eucrites could have formed by different

degrees of partial melting from a similar source material only if the source were quite different from that proposed for non-cumulate eucrites.

The sample of clast No. 4 that was analysed has a REE pattern very similar to that of Moore County, but has a smaller Eu excess and is slightly more enriched in heavy REE relative to light REE. REE were measured in the sample of clast No. 4 remaining after sample loss had occurred and, according to major element analyses, the remaining sample had a higher pyroxene, ~62%, and lower plagioclase, ~36%, content than the initial, entire sample, ~56 and ~38%, respectively. Because of the way in which REE partition themselves between co-crystallizing pyroxene and plagioclase, it is clear that a correction for the loss of plagioclase relative to pyroxene during sample loss would result in a slightly greater Eu excess and a slightly lower Lu/La ratio for the original sample than the one actually analysed for REE. Thus, the bulk clast probably has a REE pattern which is in closer agreement with that of Moore County than is that of the sample analysed and plotted in Fig. 9. According to the model of CONSOLMAGNO and DRAKE (1977) then, clast No. 4 would represent the material solidifying after ~85% fractional crystallization of a melt having the composition of the main eucrite group. Under these circumstances, its plagioclase should be no more albitic than An_{90} and its atomic $\text{FeO}/\text{FeO} + \text{MgO}$ ratio no higher than 0.50, the values characteristic of Moore County, if the two objects were derived from the same parent liquid. In this regard, the apparent atomic $\text{FeO}/\text{FeO} + \text{MgO}$ ratio of clast No. 4 presents a problem. Using the FeO value computed for the bulk clast prior to sample loss, this ratio is 0.54 ± 0.02 . Considering that this value is highly dependent on the mean composition adopted for the pyroxene in the clast, however, it cannot be concluded with certainty that the ratio is actually greater than 0.50. The plagioclase composition in clast No. 4 presents a more severe problem. Although some plagioclase grains in it are in the range An_{90} – An_{91} , most are more albitic and the mean composition is An_{86} . It also appears that the bulk Sc content of clast No. 4 is significantly higher than that of Moore County, 24 ppm (SCHMITT *et al.*, 1972), and that the clast's TiO_2 content is considerably higher than Moore County's (Table 1). The TiO_2 and Sc contents of clast No. 4, the Ab content of its plagioclase and possibly also its $\text{FeO}/\text{FeO} + \text{MgO}$ ratio suggest that it crystallized from a more highly differentiated liquid than that responsible for Moore County: yet the REE patterns of clast No. 4 and Moore County are the same. Because absolute concentrations of REE increase or decrease with Sc and Na_2O contents and $\text{FeO}/\text{FeO} + \text{MgO}$ ratios in liquids produced by partial melting or fractional crystallization, Moore County and clast No. 4 could not have formed by such processes acting on the same source material. If CONSOLMAGNO and DRAKE (1977) are correct in their assertion that Moore County

formed after fractional crystallization from a melt having the composition of the main eucrite group and if clast No. 4 formed as a result of the same series of processes, the liquid that gave rise to clast No. 4 could not have been derived from the same source material as the main eucrite group and, therefore, the bulk of ALHA 76005.

Although the FeO/FeO + MgO ratio of the pyroxene in clast No. 4 is probably slightly greater than that of Moore County pyroxene, it is still not nearly large enough to have formed from the same parent liquid as Serra de Magé after the additional degree of fractional crystallization indicated by the REE patterns, according to the calculations of MA and SCHMITT (1979). Thus, if MA and SCHMITT (1979) are correct, clast No. 4, like Moore County, could only be derived from the same source material as Serra de Magé if that source material were quite different from that of the non-cumulate eucrites and, therefore, the bulk of ALHA 76005.

A discrepancy exists in that the REE pattern of clast No. 4 is that of a cumulate eucrite, but the ophitic texture of this clast is distinctly unlike that of a cumulate. There are two possible explanations. First, according to both models of cumulate petrogenesis (CONSOLMAGNO and DRAKE, 1977; MA and SCHMITT, 1979), production of the REE pattern of clast No. 4 requires a certain amount of fractional crystallization from a particular type of liquid prior to crystallization of the pyroxene and plagioclase seen in this clast. It does not require physical formation of a cumulate, only that the crystals be strongly concentrated relative to their host liquid. The texture of clast No. 4 suggests that only ~10% interstitial liquid was present. Such a rock could have formed in an environment such as a dike, for example, after the required amount of fractional crystallization had taken place. Second, a rock having both the textures and chemistry of a cumulate could have been re-melted isochemically during impact and could have solidified to form an ophitic rock of which clast No. 4 is a fragment.

OXYGEN ISOTOPIC COMPOSITION

CLAYTON *et al.* (1979) reported oxygen isotopic data for ALHA 76005, which they called AN5, and for clast No. 4, which they called an 'anorthositic clast'. Data for the bulk meteorite, $\delta^{18}\text{O} = 3.96$ and $\delta^{17}\text{O} = 1.78$, are consistent with its derivation by partial melting of the same source as the main eucrite group. Clast No. 4, however, has lower $\delta^{18}\text{O}$, 3.55, and higher $\delta^{17}\text{O}$, 1.97, than its host and cannot be related to it or the main eucrite group by an igneous fractionation process. The oxygen isotopic and chemical data are thus in agreement on this point.

An argument could be made that the clast and its host differ in oxygen isotopic composition because they contain different amounts of admixed material from a meteoritic projectile. From the positions of

clast No. 4, the bulk meteorite and other meteorite types on a plot of $\delta^{17}\text{O}$ vs $\delta^{18}\text{O}$ (CLAYTON *et al.*, 1976, 1979), it is seen that the oxygen isotopic compositions of clast and host could only be related in this way if the bulk meteorite contains more C2 chondrite material than the clast, as this is the only meteorite type whose bulk isotopic composition lies close to the extension of the line between the clast and its host. Although it is not known precisely where bulk C2 chondrites lie on this diagram, CLAYTON and MAYEDA (1978) have measured the oxygen isotopic composition of a lithic fragment of C2 bulk chemical composition and mineralogy (FODOR and KEIL, 1976) in the Plainview H-group chondrite. It has a $\delta^{18}\text{O}$ of 6.6 and a $\delta^{17}\text{O}$ of 1.2, values which could conceivably be representative of bulk meteorites of the C2 chondrite group. Using the isotopic composition of the Plainview clast as that of the added component leads to the conclusion that 13% C2 chondrite material would have to be added to clast No. 4 to yield the isotopic composition of the bulk of ALHA 76005. C2 chondrites are highly enriched in such elements as Co and Au compared to achondrites. Thus, from the above calculation, one would expect the bulk meteorite to have higher concentrations of these elements than the clast. From Table 1, however, the bulk meteorite contains far *less* Co than the clast. Although the bulk does contain higher Au than the clast, the calculation would predict about 22 ppb in the host, compared to the observed value of only 9 ppb. We conclude that there is no known meteorite type which, when added to clast No. 4, would yield the combination of oxygen isotopic and trace element composition observed in the bulk of ALHA 76005. Rather, the clast and its host appear to be intrinsically different in oxygen isotopic composition.

It is difficult to imagine that a small eucrite parent body underwent the kind of igneous processing implied by the existence of a related series of rocks consisting of the main eucrite group and Nuevo Laredo and, at the same time, harbored another series of rocks including clast No. 4 against oxygen isotopic exchange with the first series. The oxygen isotopic results may thus imply that clast No. 4 did not even originate on the same parent body as the other eucrites.

CONCLUSION

In hand specimen, eucrites are seen to be dark rocks that contain clasts embedded in a fine-grained matrix. Augite and pigeonite are the dominant pyroxenes. Viewed in the same way, howardites are seen to contain clasts of light green or yellow magnesian orthopyroxene in addition to the dark clinopyroxenes of the eucrites. Thus, it was easy for WAHL (1952) to distinguish howardites from eucrites on the basis of their appearance when he introduced the terms poly-mict and monomict to describe them. He used the

term monomict for "brecciated stony meteorites [that] contain only material of one and the same kind and seem to have been formed by... crushing of an earlier formed homogeneous stony meteorite." Polymict was used for "brecciated stony meteorites [that]... contain fragments of different kinds." DUKE and SILVER (1967) used the same criteria to distinguish howardites from eucrites, but found that, in achondritic monomict breccias, "the lithic fragments have essentially identical mineral compositions and a limited textural variety" and interpreted this to mean that "each breccia apparently represents only a limited environment of the original magmatic setting." Similarly, they interpreted the wide range of mineral compositions and textures of the lithic fragments within individual achondritic polymict breccias in terms of sampling of "rocks from a wide variety of original crystallization and recrystallization sites." In introducing the concept that polymict breccias contain lithic clasts that formed in different magmatic settings or crystallization sites, DUKE and SILVER (1967) departed from WAHL'S (1952) original distinction between howardites and eucrites which was based on visible differences. In this work and that of MIYAMOTO *et al.* (1979a), achondritic breccias are described which lack the coarse light green or yellow orthopyroxenes so obvious to DUKE and SILVER (1967) in the howardites; yet, contain fragments which differ from one another in texture and mineral chemistry, implying different physico-chemical conditions of formation. According to DUKE and SILVER'S (1967) usage, such meteorites are polymict, though not howardites. Care must therefore be exercised in making generalizations about eucrite petrogenesis, as some eucrites contain igneous materials with different origins and histories.

The question arises as to the precise meaning of the widely-used terms monomict and polymict. Is a rock monomict if it contains fragments of rocks formed at different times and widely separated places, but which closely resemble one another in mineral proportions, texture and chemical composition? How wide a range of mineral composition and textural variety should be permitted in a monomict breccia? Is a rock polymict if it contains fragments from different portions of the same lava flow, such as the fine-grained, glassy chill zone and the coarser-grained ophitic interior? Or, must a polymict breccia contain fragments from at least different structural units? Can the different structural units be part of the same magmatic complex, such as anorthosite and pyroxenite bands from a layered igneous intrusion? Although many achondrites have been called polymict in the literature, we are unaware of any case in which the above distinctions could have been made with certainty. In this paper, we have shown that clast No. 4, though similar to the bulk of ALHA 76005 in mineralogy and mineral chemistry, could not have come from the same magmatic complex. In the literature of achondrites, how often has petrographic similarity between a clast

and its host been the criterion for labelling a breccia monomict, thereby discouraging further study?

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REFERENCES

- CLAYTON R. N. and MAYEDA T. K. (1978) Multiple parent bodies of polymict brecciated meteorites. *Geochim. Cosmochim. Acta* **42**, 325–327.
- CLAYTON R. N., ONUMA N. and MAYEDA T. K. (1976) A classification of meteorites based on oxygen isotopes. *Earth Planet. Sci. Lett.* **30**, 10–18.
- CLAYTON R. N., MAYEDA T. K. and ONUMA N. (1979) Oxygen isotopic compositions of some Antarctic meteorites. *Lunar Planet. Sci. X*, pp. 221–223.
- CONSOLMAGNO G. J. and DRAKE M. J. (1977) Composition and evolution of the eucrite parent body: evidence from rare earth elements. *Geochim. Cosmochim. Acta* **41**, 1271–1282.
- DAVIS A. M., ALLEN J. M., HUTCHEON I. D. and GROSSMAN L. (1978) A hibonite-rich inclusion from Allende: mineralogy, texture and trace element chemistry. *Lunar Planet. Sci. IX*, pp. 221–223.
- DUKE M. B. and SILVER L. T. (1967) Petrology of eucrites, howardites and mesosiderites. *Geochim. Cosmochim. Acta* **31**, 1637–1665.
- FODOR R. V. and KEIL K. (1976) Carbonaceous and non-carbonaceous lithic fragments in the Plainview, Texas, chondrite: origin and history. *Geochim. Cosmochim. Acta* **40**, 177–189.
- GARCIA D. J. and PRINZ M. (1978) The Binda orthopyroxene cumulate eucrite. *Meteoritics* **13**, 473.
- GAST P. W. and HUBBARD N. J. (1970) Rare earth abundances in soil and rocks from the Ocean of Storms. *Earth Planet. Sci. Lett.* **10**, 94–101.
- GAST P. W., HUBBARD N. J. and WIESMANN H. (1970) Chemical composition and petrogenesis of basalts from Tranquility Base. *Proc. Apollo 11 Lunar Sci. Conf.*, pp. 1143–1163.
- GROSSMAN L. and GANAPATHY R. (1976) Trace elements in the Allende meteorite—I. Coarse-grained, Ca-rich inclusions. *Geochim. Cosmochim. Acta* **40**, 331–344.
- HAMET J., NAKAMURA N., UNRUH D. M. and TATSUMOTO M. (1978) Origin and history of the adcumulate eucrite, Moama as inferred from REE abundances, Sm–Nd and U–Pb systematics. *Proc. 9th Lunar Planet. Sci. Conf.*, pp. 1115–1136.
- HASKIN L. A., FREY F. A., SCHMITT R. A. and SMITH R. H. (1966) Meteoritic, solar and terrestrial rare-earth distributions. In *Physics and Chemistry of the Earth, VII* (eds L. H. Ahrens, F. Press, S. K. Runcorn and H. C. Urey), pp. 167–321. Pergamon Press.
- LOVERING J. F. (1975) The Moama eucrite—a pyroxenoplagioclase adcumulate. *Meteoritics* **10**, 101–114.
- MA M.-S. and SCHMITT R. A. (1979) Genesis of the cumulate eucrites Serra de Magé and Moore County: a geochemical study. *Meteoritics* **14**, 81–89.
- MASON B. (1962) *Meteorites*. Wiley.
- MASON B. (1963) The hypersthene achondrites. *Am. Mus. Novitates* **2155**, 1–13.

- MASON B., JAROSEWICH E. and NELEN J. A. (1979) The pyroxene-plagioclase achondrites. *Smithsonian Contrib. Earth Sci.* **22**, 27-45.
- MCCARTHY T. S., AHRENS L. H. and ERLANK A. J. (1972) Further evidence in support of the mixing model for howardite origin. *Earth Planet. Sci. Lett.* **15**, 86-93.
- MITTFELDLT D. W. (1979) Petrographic and chemical characterization of igneous lithic clasts from mesosiderites and howardites and comparison with eucrites and diogenites. *Geochim. Cosmochim. Acta* **43**, 1917-1935.
- MIYAMOTO M., TAKEDA H. and YANAI K. (1979a) Eucritic polymict breccias from Allan Hills and Yamato Mountains, Antarctica. *Lunar Planet. Sci.* X, pp. 847-849.
- MIYAMOTO M., TAKEDA H., YANAI T. and HARAMURA H. (1979b) Mineralogical examination of the Allan Hills no. 5 meteorite. *Proc. 3rd Symp. on Antarctic Meteorites*, pp. 59-71.
- NAKAMURA N., MASUDA A., COFFRANT D. and TATSUMOTO M. (1979) REE abundances and Sm-Nd systematics of Antarctic eucrite, Allan Hills no. 5 meteorite. *Meteoritics* **14**, 492-493.
- OLSEN E. J., NOONAN A., FREDRIKSSON K., JAROSEWICH E. and MORELAND G. (1978) Eleven new meteorites from Antarctica, 1976-1977. *Meteoritics* **13**, 209-225.
- PALME H., BADDENHAUSEN H., BLUM K., CENDALES M., DREIBUS G., HOFMEISTER H., KRUSE H., PALME C., SPETTEL B., VILCSEK E. and WÄNKE H. (1978) New data on lunar samples and achondrites and a comparison of the least fractionated samples from the earth, the moon and the eucrite parent body. *Proc. 9th Lunar Planet. Sci. Conf.*, pp. 25-57.
- PERLMAN I. and ASARO F. (1969) Pottery analysis by neutron activation. *Archaeometry* **11**, 21-52.
- PRIOR G. T. (1920) The classification of meteorites. *Mineral. Mag.* **19**, 51-63.
- SCHMITT R. A., GOLES G. G., SMITH R. H. and OSBORN T. N. (1972) Elemental abundances in stone meteorites. *Meteoritics* **7**, 131-213.
- SCHNETZLER C. C. and PHILPOTTS J. A. (1969) Genesis of the calcium-rich achondrites in light of rare-earth and barium concentrations. In *Meteorite Research* (ed. P. Millman), pp. 206-216. D. Reidel.
- STOLPER E. (1977) Experimental petrology of eucritic meteorites. *Geochim. Cosmochim. Acta* **41**, 587-611.
- TAKEDA H., MIYAMOTO M., YANAI K. and HARAMURA H. (1978) A preliminary mineralogical examination of the Yamato-74 achondrites. *Proc. 2nd Symp. on Yamato Meteorites*, pp. 170-184.
- YAGI K., LOVERING J. F., SHIMA M. and OKADA A. (1978) Mineralogical and petrological studies of the Yamato meteorites, Yamato-7301(j), -7305(k), -7308(l) and -7303(m) from Antarctica. *Proc. 2nd Symp. on Yamato Meteorites*, pp. 121-141.
- WAHL W. (1952) The brecciated stony meteorites and meteorites containing foreign fragments. *Geochim. Cosmochim. Acta* **2**, 91-117.