MINERALOGICAL COMPARISON OF ANTARCTIC AND NON-ANTARCTIC HED (HOWARDITES-EUCRITES-DIOGENITES) ACHONDRITES

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Abstract: Mineralogical examination of thin sections of non-Antarctic and Antarctic HED (howardite, eucrite, diogenite) achondrites indicates that they contain a variety of lithic components. Some of these components occur both as monomict meteorites and as clasts in polymict meteorites, whereas others occur only as clasts in some polymict breccias. The components may be classified by the degree of homogenization of the pyroxene present. In order of increasing homogeneity these are: (1) Y-75011-type basalt clasts; (2) Pasamonte; (3) Y-790266-type clasts; (4) Stannern and Nuevo Laredo; (5) Juvinas and Haraiya; and (6) Ibitira (?). Type 1 has been least modified by post-igneous thermal annealing, while types 5 and 6 were thoroughly metamorphosed. Three types of cumulate eucrites are recognized and are believed to represent (a) cumulates from thick lava flows or layered intrusions; (b) lunar highlands type crust; and (c) differentiation products of diogenitic magmas.

1. Introduction

Howardites, eucrites and diogenites are a suite of meteorites with closely related mineralogy, petrology and chemistry (DUKE and SILVER, 1967). It was proposed that they developed on the same parent body (CONSOLMAGNO and DRAKE, 1977; TAKEDA, 1979). We call these meteorites HED achondrites in this paper. Previous studies of HED achondrites have been reviewed by MASON *et al.* (1979) and have helped elucidate the nature of Antarctic achondrites. The large number of Antarctic HED achondrites specimens have contributed to further evidence that can be used to reconstruct their parent body and to help deduce their origin and evolution (*e.g.* TAKEDA *et al.*, 1979, 1980; GROSSMAN *et al.*, 1981; BASALTIC VOLCANISM STUDY PROJECT, 1981; DELANEY *et al.*, 1983a, b).

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There are marked differences between the Antarctic and non-Antarctic achondrite collections as reviewed by REID (1982). Diogenites and polymict eucrites are more abundant in the Antarctic collections; however, it has been proposed that many of them are fragments of the same meteorite (TAKEDA *et al.*, 1981a; WOODEN *et al.*, 1983). Some of them belong to uncommon varieties. Thus, conclusions deduced from the study of only Antarctic HED achondrites may be biased. To gain a better understanding of the parent body we carried out a comparative study of the Antarctic and non-Antarctic HED meteorites. This paper reports on some of the results of the comparison, together with a reviews of relevant Antarctic specimens.

In addition, comparison of ordinary eucrites and basaltic clasts in Antarctic polymict eucrites enable us to propose a scale of 'degree of homogenization of eucritic pyxenes'. Ordinary eucrites are known for the uniform bulk compositions of their pigeonites, which include exsolved augite and dusty ilmenite inclusions. These meteorites have been subjected to extended subsolidus annealing (TAKEDA *et al.*, 1978). Pasamonte is an example of quickly cooled lava-like eucrite, which contains chemically zoned pyroxene, and is comparable to lunar mare basalts (TAKEDA *et al.*, 1976a). Fragments of such basalts are found in many Antarctic polymict eucrites and their genetic relationships have been discussed by DELANEY *et al.* (1983b). REID and BARNARD (1979) used the terms unequilibrated and equilibrated eucrites to distinguish these two classes of meteorites. We found that eucrites, such as Y-790266, Stannern, and Nuevo Laredo are intermediate between these two ends of a scale. In this paper, we emphasize that Antarctic and non-Antarctic eucrites sample a continuum of basalt types ranging from least-altered basalt, to partially homogenized basalt, to totally homogenized ordinary eucrites on a scale of 'degree of homogenization' of eucritic pyroxene.

2. Samples and Experimental Techniques

Polished thin sections of Antarctic specimens were made available for this study by the National Institute of Polar Research (NIPR) in Japan and the Meteorite Working Group of the United States. The polished thin sections analyzed, in this United States-Japan cooperative research study, include Y-74450,63, Y-75011,84, Y-75015,20, Y-74159,71, Y-74159,PB, Y-7308, Allan Hills-765, ALH-78006,10, ALH-78158,81 and ALH-78165,91. Yamato-79 PET (Preliminary Examination Team) sections Y-790007, Y-790020, Y-790260 and Y-790266 were also made available by NIPR.

Non-Antarctic HED achondrites were studied in polished thin sections obtained from the American Museum of Natural History (AMNH) and the National Museum of Natural History, Smithsonian Institution (NMNH). These used for microscopic observation include Johnstown (AMNH 2497–3), Shalka (546–1, 546–2), Binda (4008–1), Serra de Magé (3786–6), Moore Co. (4471–6), Juvinas (466–5), Stannern (1058–1), Sioux Co. (4133–1), Haraiya (4062–2), Chevony Kut (4473–2) Pasamonte (4460–1), Nuevo Laredo (4107–1), and Nagaria (NMNH 2434).

Chemical analyses were carried out on a fully automated nine channel ARL-SEMQ electron microprobe at AMNH. This procedure was briefly described in PRINZ *et al.* (1980). Chemical zoning and phases unmixed by exsolution in pyroxenes were examined by measuring the Ca, Mg and Fe concentrations by scanning or at 5 to 50 μm intervals, with a JEOL JXA-5 electron-probe X-ray microanalyzer with a 40° take-off angle. Quantitative chemical analyses were made with a JEOL 733 super probe at the Ocean Research Institute of the University of Tokyo, by employing the same parameters as those used with the JXA-5. The method is the same as that of NAKAMURA and KUSHIRO (1970).

Pyroxene crystals were examined with an X-ray precession camera to identify the orientation and the presence of coexisting phases. *h0l* and *0kl* or *hk0* nets were taken using Zr-filtered Mo Kα radiation. After X-ray study, crystals were mounted in thick resin with the *b* axis perpendicular to the plane of a glass slide, and polished to about a 10 μm thickness. Each crystal was removed from the glass slide and glued to a 3 mm molybdenum grid of transmission electron microscopy (TEM) for support and was thinned in an Edwards ion-thinning machine until perforation occurred. Examination on microtextures of the ion-thinned samples was carried out with a Hitachi analytical transmission electron microscope (ATEM) (H-600) equipped with a Kevex Energy Dispersive Spectrometer (EDS) (MORI and TAKEDA, 1982; TAKEDA *et al.*, 1981b).

3. Results

3.1. Diogenites

Chromite crystals in the Y-74013-type diogenite are much coarser than the typical granoblastic orthopyroxene crystals and are thought to be relict from an earlier igneous texture of the original diogenite crystallization. A search for such chromites among non-Antarctic diogenites was made among the thin sections at AMNH. Similar chromite was found in a crystalline clast of Shalka (Fig. 1). The crystals (1.4 × 0.9 mm) are dark brown and are not as large as those in Y-74013 (up to 5 mm in diameter); they are about half as long as the coexisting orthopyroxene crystals (up to 3 mm) and are larger than those in the Johnstown diogenite (0.6 × 0.35 mm). In all thin sections examined, the largest orthopyroxene crystals are larger than the largest chromite crystals.

Other Yamato diogenites, represented by Y-75032, are more iron-rich than non-Antarctic diogenites, and are similar to the most magnesian cumulate eucrite Binda. Since the abundance of plagioclase sets the boundary between diogenite and eucrite, we measured the modal abundance of minerals in other small specimens of this type which were recognized in the Yamato-79 collection (TAKEDA and YANAI, 1982). They contain dark brown glass in the interstices between fragmented pyroxenes. The modal abundance of plagioclase in some of these meteorites exceeds the 10% limit of diogenite, so they are not strictly pyroxenites. At least one specimen contains a clast of gabbroic eucrite similar to Binda and Moama. The most iron-rich pyroxene in the matrix approaches Fs_{50} and has (001) platy lamellae rather than blebs.

3.2. Howardites

Two new thin sections of Y-7308 have been examined modally and petrographically. Some of the results of the study of lithological components present in this breccia, and their relationship to other basaltic achondrites, are given in NEHRU *et al.* (1983). Modes of this howardite have a greater abundance of low-Ca pyroxene (76 vol %) and olivine (1.8%) than any other howardite yet studied.

Among the components contained in Y-7308 (NEHRU *et al.*, 1983), orthopyroxenite is the most abundant and important. The compositional range of the mineral clasts is biased towards more magnesian compositions. One of several noteworthy features is the presence of magnesian mafic clasts close to the gap in Mg/(Mg+Fe) ratio between the cumulate eucrites and diogenites. They are similar to those found in Y-75032 and related cumulate eucrites in the Y-79 collection (TAKEDA and YANAI, 1982). Iron-rich basalts of the ordinary eucrite-type were rather rare. An augite-bearing gabbroic rock is also present.

3.3. Cumulate eucrites

Microscopic examination of Binda, Serra de Magé, Moore County and Nagaria confirmed our earlier observations made on pyroxene single crystals (TAKEDA, 1979; HARLOW *et al.*, 1979). We restate below the characteristics of two type of cumulate eucrites, including some new results.

Binda has different textures of inverted pigeonite and a lesser modal abundance of plagioclase than cumulate eucrites of the Moore Co. type. The pyroxene of Binda (AMNH, 4008–1) exhibits blebby inclusions of augite elongated along one direction (mostly *c*) (Fig. 2) as was observed on single crystals (TAKEDA, 1979). The augite blebs share (100) with the host orthopyroxene in most cases, although there are some exceptions. The presence of primary orthopyroxene cannot be excluded. Binda has pyroxene textures similar to Moama, but all the pyroxene in Moama is low-Ca inverted pigeonite. Moama is crystalline and has higher modal plagioclase.

Serra de Magé was reported to contain two types of inverted pigeonite similar to Moama and Moore Co., respectively (HARLOW *et al.*, 1979). Observation of a new thin section at AMNH reveals that it all belongs to the Moore Co. type. Apparent Binda-type inverted pigeonite with blebby augite inclusions is actually inverted pigeonite of the host phase between (001) augite lamellae of Moore Co. type (Fig. 3a). Moore Co. is plagioclase-rich, and exsolved augite in the pyroxene forms thick (up to 100 μm in width) lamellae with (001) in common with the host pigeonite, which is partly to completely inverted to orthopyroxene. Serra de Magé pyroxene is totally inverted.

The texture in the thin section of Serra de Magé (AMNH-3786–6) reveals a mechanism of transformation of pigeonite into orthopyroxene. The parallel lamellae of augite, which are relict augite lamellae produced in primary pigeonite with (001) in common, reveal the grain boundaries of the original pigeonite crystals (Fig. 3b). These boundaries are different from those of orthopyroxenes inverted from pigeonite, which are shown by the common extinction angle in cross polarized light. An orthopyroxene crystal nucleated in one crystal of primary pigeonite grew into another pigeonite crystal. This texture is indicative of grain-coarsening during or after inversion.

The orientation of augite blebs within one pigeonite crystal differs from one domain to another (Fig. 3a). Preferred orientation of the blebs is interpreted to be the result of a 'pearlite transformation', or decomposition at or a little below the pigeonite eutectoid reaction (PER) line (ISHII and TAKEDA, 1974). When an augite bleb is nucleated in the pigeonite host by decomposition, the augite and orthopyroxene may grow with (100) in common around the bleb. This produces high-Ca sites that favor further nucleation of more augite blebs around them. This mechanism permits pres-

Fig. 1a. Photomicrograph of a large chromite crystal found in a crystalline clast of Shalka. Open. Width is 3.2 mm.

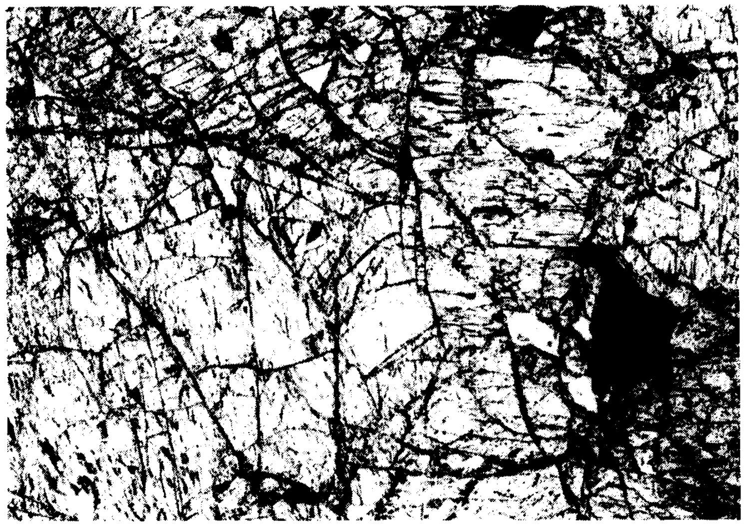

Fig. 1b. Small chromite in Johnstown. Open. Width is 3.2 mm.

Fig. 1c. The same as above. Cross polarized light.

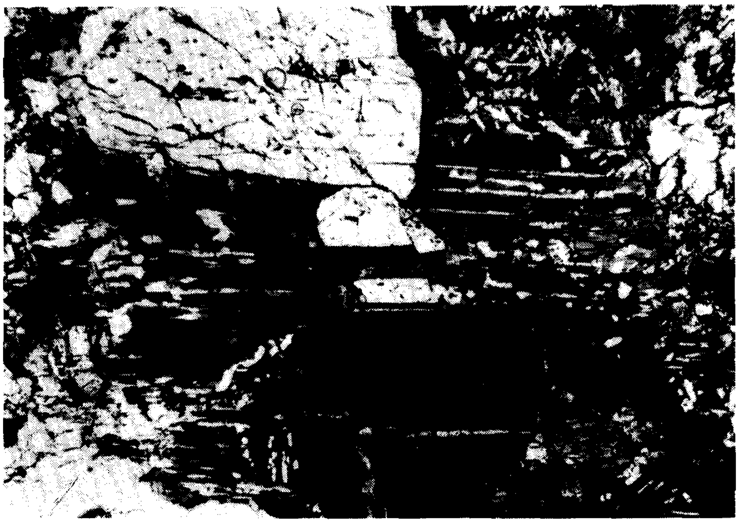

Fig. 2. Photomicrograph of Binda. Low-Ca inverted pigeonite with blebby inclusions of augite. Cross polarized light. Width is 3.2 mm.

Fig. 3a. Photomicrograph of an inverted pigeonite from Serra de Magé. Width is 2.0 mm. Cross polarized light. Note orientations of augite blebs between the (001) augite lamellae.

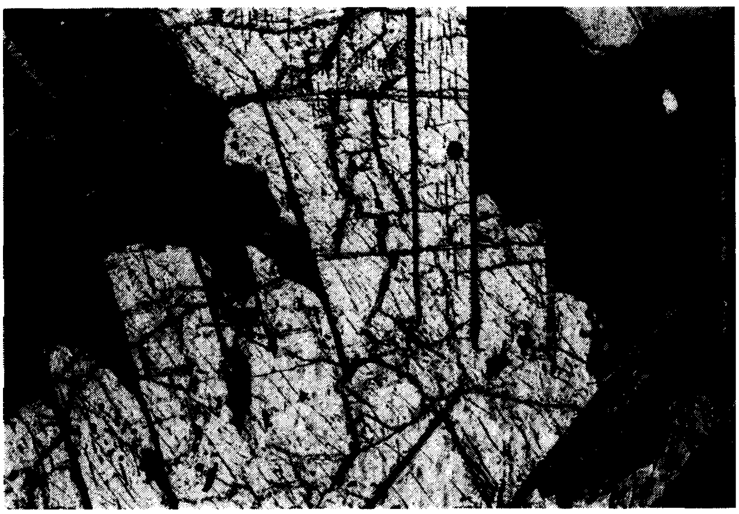

Fig. 3b. The same as above, but with low magnification. Width is 3.2 mm. Lamellae are relicts of 4 different orientations of (001) augites. The white orthopyroxene region grows into other crystals of original pigeonites.

Fig. 4. Photomicrograph of partly inverted pigeonites from Moore County. Herring-bone shaped lamellae indicate twinning. The dark areas are orthopyroxenes inverted from a pigeonite. Cross polarized light. Width is 3.2 mm.

Fig. 5. Photomicrograph of partly inverted pigeonite from Nagaria. Herring-bone shaped lamellae are remnant (001) augites exsolved from the original twinned pigeonite. The dark host is partly inverted to orthopyroxene. Width is 0.62 mm. Cross polarized light.

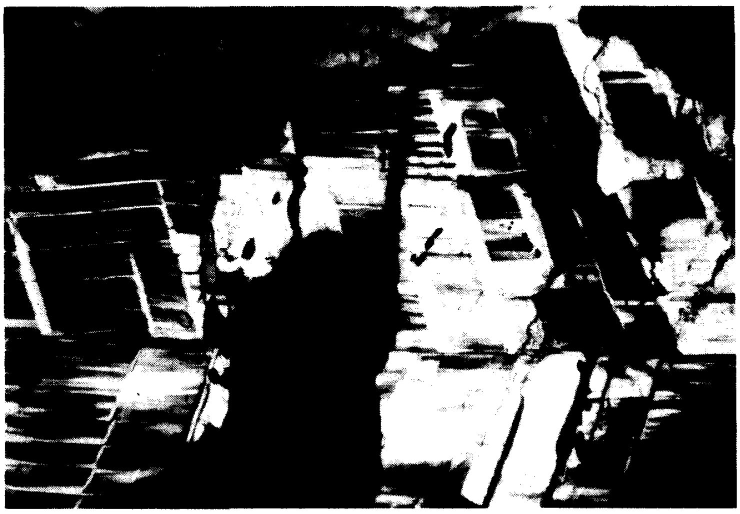

Fig. 6. Photomicrograph of twinned inverted pigeonite from Allan Hills 78006 polymict eucrite. Note similarity to that of Nagaria in Fig. 5. Cross polarized light. Width is 0.62 mm.

ervation of a common orientation of the blebs within a single domain in agreement with our observation. The presence of different domains within a single orthopyroxene crystal may indicate that grain-coarsening of orthopyroxene took place after inversion. If so, the constant orientation of augite blebs and the original host orthopyroxene may not be preserved in some domains (Fig. 3a).

Thin sections of Moore Co. reveal the same features (Fig. 4) as described by HESS and HENDERSON (1949), MASON *et al.* (1979) and MORI and TAKEDA (1981a) except the following. A small area within a single crystal is completely transformed to orthopyroxene with blebby augite inclusions. The orientation of this orthopyroxene is different from that in a partly inverted portion with (100) in common. The partly inverted portions have slightly lower Ca contents ($Ca_{3.2}Mg_{50.3}Fe_{46.5}$) than the uninverted portions ($Ca_5Mg_{47}Fe_{48}$). Pyroxene grains of Nagaria also show partly inverted textures, but the augite lamella width is an order of magnitude thinner than those in Moore Co. (Fig. 5). ALH-78006 contains partly inverted pigeonite very similar to Nagaria, as shown in Fig. 6.

3.4. *Ordinary eucrites*

3.4.1. Slowly cooled main group eucrites

Juvinas, Sioux Co. and Haraiya show relatively slowly cooled textures. Mineral grains are more equigranular than in other main group eucrites. However, a lamella-like linear texture is found which consists of linearly aligned precipitates of ilmenite known as clouding (HARLOW and KLIMENDITIS, 1980). This linear texture was previously thought to be augite lamellae. Augite lamellae are not visible under the microscope, except in Haraiya, and the true width of augite lamellae in Juvinas measured by TEM technique is thinner than that previously reported (MIYAMOTO and TAKEDA, 1977), and ranges from 0.2 to 0.4 μm. The compositions of the host-lamellae (H-L) pair in Juvinas (Fig. 7) obtained by ATEM are those of a low-temperature pair (LINDSLEY and ANDERSON, 1983).

The thickest lamella-like texture visible under the microscope has been found in Haraiya (Fig. 8). An electron microprobe scan monitoring Ca, Mg, and Fe $K\alpha$ radiation reveals that exsolution lamellae of augite have widths from 5 μm to 1 μm with 5 to 20 μm intervals.

Chervony Kut has an unbrecciated equigranular texture (GOODING *et al.*, 1979). A large crystal of chromite has been found as shown in Fig. 9. Fragments of sub-mm sized chromite have occasionally been found in Antarctic polymict eucrites, but are rare in crystalline eucrites.

3.4.2. Stannern-type eucrites

Because of the textural similarity between Stannern and basaltic clasts in Y-75011, 84, we searched for evidence of remnant chemical zoning of pyroxene and metamorphosed mesostasis in Stannern. Other similarities include: (1) lath-shaped bytownitic plagioclase with thin cores of pigeonite and blocky pyroxene (Fig. 10a), and (2) dark, dusty, mottled areas at the junctions of pyroxene and plagioclase (Fig. 10b), which look like metamorphosed mesostasis.

The chemical trend of pyroxene varies from host pigeonite with $Ca_{1.4}Mg_{36.4}Fe_{62.2}$ to exsolved augite lamella with $Ca_{40}Mg_{31}Fe_{29}$ (Fig. 11, Table 1). However, line scan

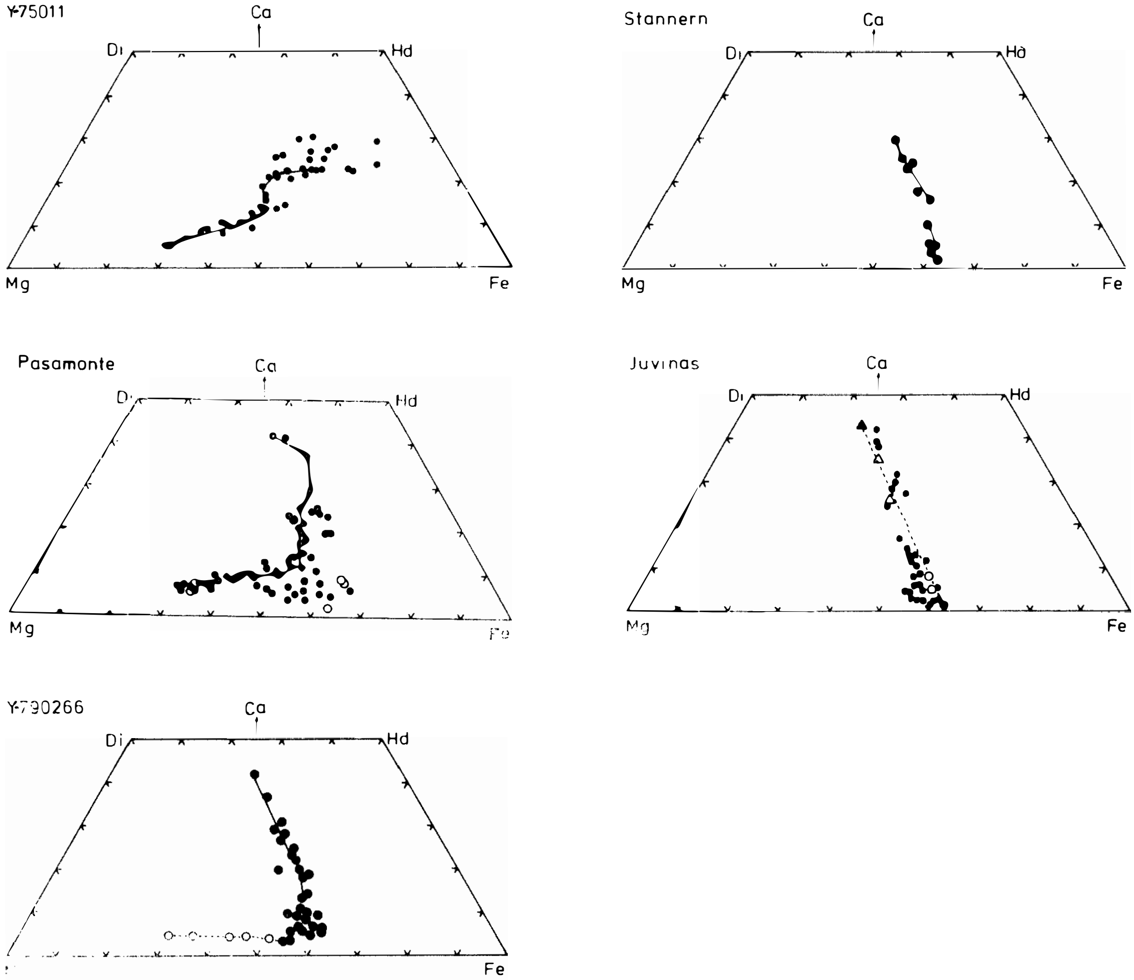

Fig. 7. Comparison of chemical zoning trends of (1) Y-75011, (2) Pasamonte, (3) Y-790266, (4) Stannern and (5) Juvinas, showing the five different degree of homogenization of pyroxenes in eucrites. Lines show a traverse from core to rim. Open circles in Y-790266 denote the trend of a tiny Mg-rich core, and those in Pasamonte are analyses of an AMNH thin section. The tie line of Juvinas connects the lemella-host (L-H) pair obtained with ATEM by MORI. Open circle: bulk; open triangle: EPMA.

Fig. 8. Photomicrograph of Haraiya. Open. Width is 0.9 mm. Vertical parallel lines are exsolved lamellae of augite.

Fig. 9. Photomicrograph of a large chromite in Chervony Kut eucrite. Open. Width is 1.0 mm.

Fig. 10a. Photomicrograph of a part of Stannern (Constatinople). Width is 3.2 mm. Open. Note the clouding in pigeonites. Original mesostasis recrystallized to coarser ilmenites, silica and troilites.

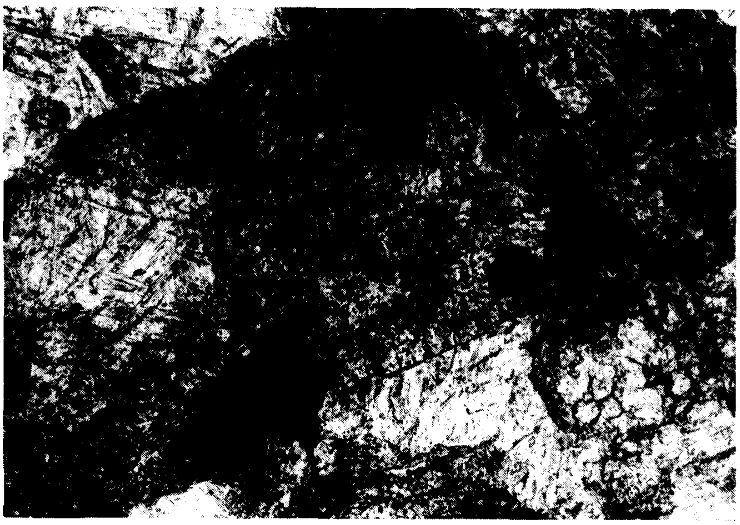

Fig. 10b. The same as above. Metamorphosed mesostasis portion. Irregular darkest minerals are ilmenites set in a dusty mottled area of troilite and silica. Width is 1.0 mm.

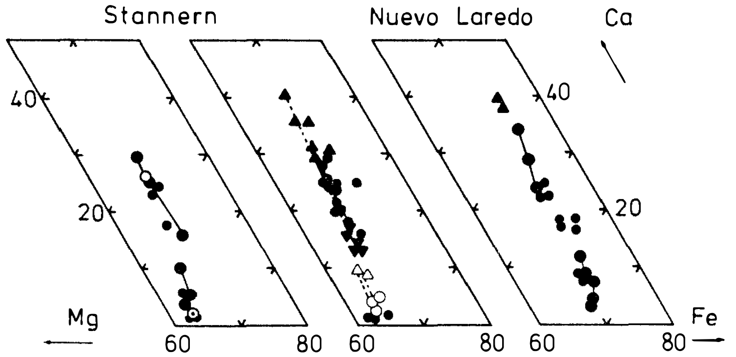

Fig. 11. A portion of pyroxene quadrilateral of Stannern and Neuvo Laredo. Stannern (left): Average compositions for every 70 μm interval of the line scan of Fig. 12 showing the remnant Ca zoning trend from rim to core. Open circle: bulk rim composition, open circle with dot: bulk core composition. (right): Host-lamella exsolution pair connected by the tie line, solid triangles: rim, open triangle and circle: core, dots: individual analyses. Note incomplete resolution of the host-lamella by EPMA. Nuevo Laredo: lines denotes zoning trend, triangle: exsolved augite, and dots: individual EPMA analyses.

Table 1. Chemical compositions (wt %) of pyroxenes from Stannern.

Remarks	Core					Rim			
	Host 1	Lam. 1	Lam. 2	Host 3	Bulk	Host 4	Lam. 4	Lam. 5	Bulk
SiO_2	48.8	48.3	50.2	49.5	49.1	49.2	49.4	49.0	49.6
Al_2O_3	0.26	0.27	0.37	0.16	0.20	0.35	0.30	0.25	0.36
TiO_2	0.15	0.48	0.14	0.12	0.30	0.24	0.40	0.21	0.29
Cr_2O_3	0.77	2.02	0.18	0.07	1.13	1.80	0.67	0.31	0.60
FeO	34.9	32.6	16.11	35.0	33.9	21.0	31.8	33.7	26.4
MnO	1.12	0.99	0.48	1.09	1.06	0.57	0.95	1.01	0.85
MgO	11.48	11.29	9.82	11.66	11.60	9.97	10.78	10.82	10.40
CaO	0.65	3.61	21.3	1.87	2.34	16.75	5.23	5.05	10.40
Na_2O	0.01	0.00	0.06	0.02	0.02	0.00	0.03	0.03	0.03
Total	98.12	99.54	98.62	99.33	99.67	99.86	100.60	100.31	98.89
Si*	1.989	1.944	1.972	1.993	1.973	1.936	1.962	1.965	1.978
Al	0.013	0.013	0.017	0.008	0.010	0.016	0.014	0.012	0.017
Ti	0.005	0.015	0.004	0.004	0.009	0.007	0.014	0.006	0.009
Cr	0.025	0.064	0.006	0.002	0.036	0.056	0.021	0.010	0.019
Fe	1.191	1.097	0.529	1.178	1.137	0.692	1.059	1.131	0.879
Mn	0.039	0.034	0.016	0.037	0.036	0.019	0.032	0.034	0.029
Mg	0.698	0.677	0.574	0.700	0.694	0.585	0.639	0.647	0.618
Ca	0.028	0.156	0.895	0.081	0.100	0.707	0.265	0.217	0.445
Na	0.001	0.000	0.004	0.001	0.001	0.000	0.002	0.002	0.003
Total	3.989	4.001	4.015	3.998	4.000	4.018	4.008	4.020	3.998
Ca**	1.5	8.1	44.8	4.1	5.2	35.6	13.5	10.9	22.9
Mg	36.4	35.1	28.7	35.7	35.9	29.5	32.6	32.4	31.8
Fe	62.1	56.9	26.5	60.2	58.9	34.9	53.9	56.7	45.3

* Cations per 6 oxygens. ** Atomic %.

Analyses Nos. 1 and 4 are values of points in the line analysis in Fig. 12.

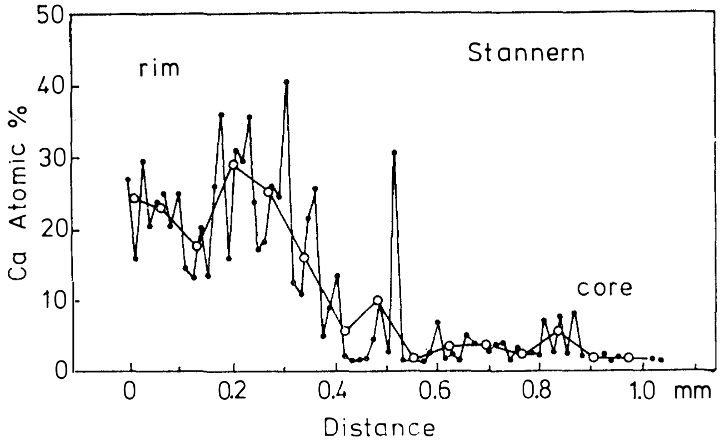

Fig. 12. Line point-analyses of Ca concentration for every 14 μm for pyroxenes from Stannern. Distances from margin at rim to core is indicated. Open circles show a trend of average for every 120 μm.

and point analyses, at a 14 μm spacing from core to rim, reveal that augite lamellae are more abundant near the rim than the core area (Fig. 12). The augite lamellae in the core are relatively broad (1 to 3 μm) and at larger spacing (20 to 30 μm), but those near the rim are almost unresolvable by an electron microprobe traverse monitoring Ca $K\alpha$ radiation, and are probably 0.2 to 0.5 μm in width with 0.3 to 1 μm intervals.

The average bulk composition in the outermost 150 μm of a crystal is $Ca_{26}Mg_{31}Fe_{43}$ and that in the center is $Ca_{1.7}Mg_{36.5}Fe_{61.8}$. This suggests that Stannern pyroxene was either originally zoned, as in the clast of Y-75011, but that the original Mg-Fe zonation was homogenized by a later thermal event. Alternately, Stannern crystallized with no zoning of Fe-Mg but with strong Ca zoning. No mechanism is known for this latter case. Plagioclase grains also preserve chemical zoning, from Ca-rich cores to more Na-rich rims (Fig. 13, Table 2). The trend is not smooth, and unusual K-rich spots occur (OR in Table 2). The high concentration of Na_2O in plagioclase is consistent with the bulk chemical composition. Unique clasts in Y-75011, Y-75015 and Y-74450 also contain more Na-rich plagioclase than in main group eucrites.

The remnant mesostasis area in Stannern is more transparent than that in the mesostasis-rich unique basaltic clasts in Y-75011. It consists of fine dusty mottled troilite and silica, augite, apatite and irregular aggregates of ilmenite and chromite (Fig. 10b). The dark-brown glassy materials and Fe-rich olivine in Y-75011 are absent in this Stannern sample.

3.4.3. Nuevo Laredo and Millbillillie

Nuevo Laredo is finer-grained (Fig. 14a) than Pasamonte, which shows extensive chemical zoning in pyroxene caused by rapid cooling. However, Nuevo Laredo pyroxene exhibits the same compositional trend as the main group eucrites. Detailed microprobe scans across many pyroxene crystals have shown that at least a part of the compositional variation of a crystal (Fig. 14b) is due to chemical zoning. Frequent Ca-rich areas observed during scanning may be attributed to augite exsolution, but the evidence is not as clear cut as for Stannern. Millbillillie is even finer-grained than Nuevo Laredo but shows the same compositional trend (FITZGERALD, 1980).

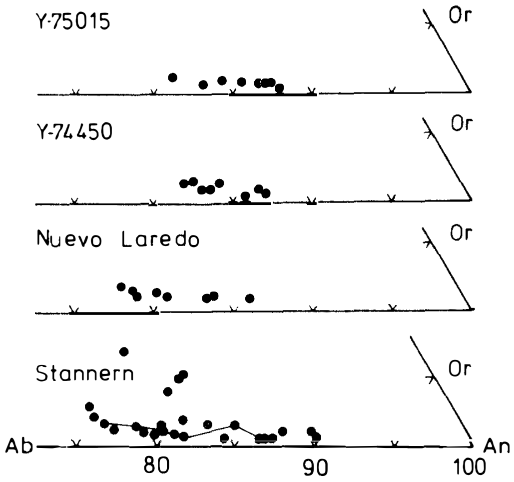

Fig. 13. Chemical compositions of plagioclases from Stannern, Nuevo Laredo, mesostasis-rich basalt clasts from Y-74450 and Y-75015.

Table 2. Chemical compositions (wt %) of plagioclase in Stannern, Nuevo Laredo and Pasamonte.

Remarks	Stannern			Nuevo Laredo		Pasamonte
	AN	AB	OR	AN	AB	AN
SiO_2	46.7	48.8	48.6	47.1	48.9	47.3
Al_2O_3	33.9	32.0	32.0	32.9	31.3	32.2
TiO_2	<0.01	<0.01	<0.03	0.00	<0.02	<0.04
FeO	0.18	0.27	<0.07	0.88	0.62	0.73
MgO	<0.01	<0.02	<0.01	0.16	0.26	0.11
CaO	16.98	15.27	15.05	16.86	15.70	17.25
Na_2O	1.71	2.60	1.55	1.76	2.37	1.55
K_2O	0.09	0.21	1.61	0.21	0.32	0.11
Total	99.62	99.26	98.87	99.91	99.43	99.31
Si*	2.153	2.249	2.254	2.172	2.256	2.193
Al	1.843	1.741	1.748	1.792	1.701	1.703
Ti	0.000	0.000	<0.001	0.000	<0.001	<0.001
Fe	<0.007	<0.010	<0.003	0.034	0.024	0.028
Mg	<0.001	<0.001	<0.001	0.011	0.018	0.007
Ca	0.839	0.754	0.748	0.834	0.776	0.857
Na	0.153	0.232	0.139	0.158	0.212	0.140
K	0.006	0.012	0.095	0.010	0.019	0.006
Total	5.003	5.001	4.989	5.015	5.007	4.996
An**	84.2	75.5	76.1	83.1	77.1	85.5
Ab	15.3	23.3	14.2	15.7	21.1	13.9
Or	0.5	1.2	9.7	1.2	1.9	0.6

* Cations per 8 oxygens
** Mol %

3.5. Surface (lava-like) eucrites

3.5.1. Y-790266

Y-790266 does not exhibit exsolution of augite within the resolution of a microscope and microprobe, and the trend of chemical zoning is from low-Ca pigeonite core to rim augite. This is termed the Fe-Ca trend. The trend (Fig. 7) of a large clast in Y-790266 can be interpreted as being partly homogenized from the original chemical zoning produced during crystallization. The presence of very rare tiny Mg-rich cores in Y-790266 (Fig. 7) supports this idea, and is interpreted to be a remnant of the initial core. This trend is different from that of Pasamonte in that most of the pyroxenes do not have Mg-rich cores.

The clouding observed in most of the ordinary eucrites is not obvious in Y-790266, but the pyroxene crystals are not as clear as those in Y-75011. TEM study of Y-790266 pyroxene shows that there is minor precipitation of ilmenite, crystallographically controlled. The size of the ilmenite platelets is an order of magnitude smaller than those in Juvinas pyroxene.

3.5.2. Pasamonte

This meteorite is the only known monomict eucrite that preserves chemical zoning produced during crystallization (TAKEDA *et al.*, 1976a). After studying a pristine basaltic clast in Y-75011, which preserves unhomogenized chemical zoning (Fig. 7) comparable to that produced by dynamic crystallization experiments (WALKER *et al.*, 1978; POWELL *et al.*, 1980), we suspect that even Pasamonte pyroxene has experienced some thermal annealing. Reexamination of Pasamonte (Fig. 15) confirms the absence of Fe-rich pyroxene beyond the host-lamellae (H-L) tie-line of main group eucrites (Fig. 7). This missing pyroxene is within the 'forbidden' zone of pyroxene (LINDSLEY and MUNOZ, 1969). Therefore, the Mg-Fe-Ca trend of Pasamonte-like pyroxene in eucrites may well be a slightly homogenized variety.

3.5.3. Quickly cooled basaltic clasts

Because Pasamonte has the most rapid igneous cooling found in the non-Antarctic collections, we looked for more quickly cooled basalts in Antarctic polymict eucrites. We observed that these contain varieties of basaltic clasts that range from pigeonite vitrophyres, porphyritic basalt with hollow Mg-rich pigeonite phenocrysts and a feathery matrix of Fe-rich pigeonite and plagioclase, variolitic, ophitic to subophitic basalts with mesostasis, to equigranular basalts. Vitrophyres and porphyritic varieties (*e. g.* Y-74450, ALH-77302) are rare among non-Antarctic main group eucrites. The chemical zoning trend and textures of the Y-75011 clast (Fig. 7) are the most pristine basalt type. It preserves the original chemical zoning developed during crystallization (TAKEDA *et al.*, 1983).

A photomicrograph of a dark clast in Y-74159 is given in Fig. 16. Its fine-grained feathery spherulitic texture indicates rapid cooling. Some other dark clasts in Y-74159 contain fragments of relict minerals set in a dark glassy matrix. This clast may be an impact melt.

4. Discussion

The comparative study of REID (1982) emphasized the differences between Antarctic and non-Antarctic achondrites. Monomict and cumulate eucrites and diogenites, and howardites dominate the non-Antarctic collections whereas polymict eucrites and unusual diogenites dominate the Antarctic collections. Many of the Antarctic specimens are, however, multiple samples from a small number of falls (TAKEDA *et al.*, 1981

Fig. 14a. Photomicrograph of Nuevo Laredo. Fine-grained texture of a larger area than that in Fig. 14b. Width is 3.2 mm.

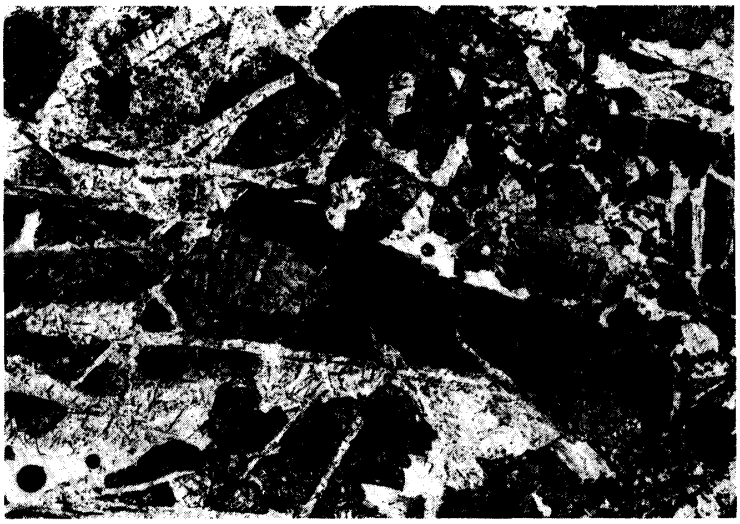

Fig. 14b. A pyroxene crystal which reveals chemical zoning from core to rim. Width is 1.0 mm.

Fig. 15. Photomicrograph of Pasamonte. Open. Width is 2.0 mm.

Fig. 16. Photomicrograph of a dark clast in the Y-74159 polymict eucrite. Open. Width is 1.0 mm.

a; WOODEN *et al.*, 1981; SHIMIZU and MASUDA, 1982). Most of the Antarctic polymict eucrite specimens contain no diogenitic fraction. Using the nomenclature scheme of DELANEY *et al.* (1983c), ALH-78006 which contains a small amount of diogenitic pyroxene, is also a polymict eucrite as are a few non-Antarctic meteorites such as Macibini and Bialystok which had previously been classified as both howardites and eucrites. In this study, the lithic components present in the polymict breccias (howardites and polymict eucrites) have been shown to be unevenly distributed among the different meteorites. Some components, present in Yamato achondrites are not present in Victoria Land achondrites. Others are present in non-Antarctic meteorites but are not so abundant in Antarctic specimens.

For example, rocks dominated by low-Ca inverted pigeonites, with compositions intermediate between those of Binda and diogenites, have been found as an individual meteorites in the Yamato collection. Similar fragments have also been found in Yamato polymict eucrites. Other fragments in polymict eucrites appear to relate the meteorite groups. Large chromites in the Y-74013 diogenite are similar to those in the Shalka diogenite. Large chromite clasts exist in polymict eucrites and in the ordinary eucrite, Chervony Kut. Inverted pigeonite similar to that in Nagaria has been found in ALH-78006.

Some features intermediate between ordinary and polymict eucrites have been recognized. Chemical zoning of pigeonites of Y-790266 and Nuevo Laredo follows a trend intermediate between the two extremes shown by the Y-75011 clast and Juvinas (unzoned, but exsolved). Y-790266 pyroxene contains tiny inclusions of ilmenite, which are abundant and large in the non-Antarctic ordinary eucrites and are visible as clouding. Stannern may be the thermally processed analogue of the Y-75011 clast, with pyroxene variability between Y-790266 and Juvinas. Feldspar from these meteorites and clasts have variable but high Na_2O contents and textures, and will be described elsewhere.

4.1. Comparison within each class of the HED achondrites

We review some characteristics of the Antarctic HED achondrites and compare them with those of the non-Antarctic ones, referring to their origin and evolution.

4.1.1. Diogenites

The Antarctic diogenites extend the boundaries of the diogenite class in composition, mineral assemblage, and texture as stated in the overview of Antarctic achondrites by REID (1982). About 30 of the Yamato diogenites are granoblastic, unlike most diogenites, and indicative of extensive recrystallization. These 30 diogenites are considered to be specimens from a single fall (TAKEDA *et al.*, 1981a). They are represented by sample number Y-74013, because it is one of the largest and is the best studied sample of this group of diogenites.

One of the characteristics of the Y-74013-type diogenite is the presence of large chromite crystals up to 3 mm in diameter. The presence of such chromites among non-Antarctic diogenites was confirmed in a crystalline clast of Shalka. The Y-74013 chromite is among the most Mg-rich found in diogenites and may be a cumulate crystal.

Other Yamato diogenites, of which Y-75032 is the best described, are more iron-rich than most diogenites. Y-75032 is a heavily shocked monomict diogenite and has as its dominant phase orthopyroxene with exsolved lamellae and blebs of augite. It originally contained major primary low-Ca pigeonite now inverted to orthopyroxene and primary orthopyroxene. The composition and texture of this pyroxene is similar to the most magnesian cumulate eucrite Binda.

The rare earth abundance pattern of Y-75032 (SHIMIZU and MASUDA, 1981) is rather similar to that of Binda. Plots of En *vs.* An contents of pyroxene and plagioclase, and En *vs.* Mg/(Fe+Mg) of chromite (NEHRU *et al.*, 1980) indicate that they are similar to Binda rather than diogenites or plagioclase-cumulate eucrites such as Moama and Moore Co. This diogenite group may be a plagioclase-poor cumulate eucrite, and is transitional between diogenites and pyroxene-rich polymict cumulate eucrites. They fill in the apparent gap in pyroxene crystallization trends between diogenites and eucrites. The presence of the plagioclase-rich specimens in the Y-79 collection supports this view.

The one diogenite from the Allan Hills region (ALH-77256) is described as normal, but even this sample contains more olivine than other diogenites.

4.1.2. Howardites

Yamato-7308 was the first howardite recovered from Antarctica (TAKEDA *et al.*, 1976b). It is one of the most diogenite-rich howardites in comparison with all known non-Antarctic howardites (DUKE and SILVER, 1967; MASON *et al.*, 1979; PRINZ *et al.*, 1980; LABOTKA and PAPIKE, 1980; FUHRMAN and PAPIKE, 1981; REID, 1982). Comparison with modes of 12 other howardites confirmed earlier findings that Y-7308 has a greater abundance of low-Ca pyroxene and olivine than any other.

There are preliminary reports of other Antarctic howardites, but detailed descriptions are not yet available. The Y-790727 howardite is compositionally intermediate between diogenite and eucrite, being similar to Binda; it contains more lithic and mineral fragments of eucritic lithologies (TAKEDA and YANAI, 1982) than Y-7308. Allan Hills-78006 (TAKEDA *et al.*, 1980) and Elephant Moraine (EETA) 79005 and 79006 (REID and SCORE, 1981) contain abundant eucritic materials with only a minor diogenitic component. Their modal and mineralogical characteristics led to their reclassification as polymict eucrites (DELANEY *et al.*, 1983c; SIMON *et al.*, 1982).

4.1.3. Cumulate eucrites

The importance of Binda-type cumulate eucrites in the diogenite-eucrite continuum has been noted previously (TAKEDA *et al.*, 1976b; TAKEDA, 1979). There is no cumulate eucrite as an individual meteorite found in the Antarctic meteorite collections. The Y-75032-type diogenites rich in plagioclase found in the Yamato-79 collection may ultimately be classed as polymict cumulate eucrites, upon further study. Their pyroxenes are similar to that in Binda.

Our finding that Serra de Magé is a Moore Co.-type cumulate eucrite provides us with useful information on the differences in their inversion mechanism and cooling history.

The eutectoid decomposition of the host phase of Serra de Magé must have taken place at or a little below the stability field of pigeonite, by slow cooling, since the development of thick (001) augite lamellae along the stable solvus of pigeonite naturally leads the host pigeonite composition to that of the PER line. If the cooling had been fast, (001) augite lamellae would probably have continued growing, below the PER line, along the metastable extension of the pigeonite solvus. The low-Ca pigeonite would then have inverted to orthopyroxene.

Partly inverted pigeonite with very fine (001) augite between the very thick (001) augite lamellae in Moore Co. (Fig. 4), suggests that a rapid cooling event may have taken place during the development of the thick (001) augite, as pointed out by MORI and TAKEDA (1981a). The presence of blebby augite between thick (001) augite lamellae in Serra de Magé probably indicates a simple slow cooling event deep within the crust. HESS and HENDERSON (1949) interpreted the Moore Co. to be the product of a catastrophic event. A similar phenomenon has been proposed for Johnstown (MORI and TAKEDA, 1981b).

Moore Co. type pyroxene is very rare, or absent, in polymict eucrites. A few inverted pigeonite found in polymict eucrites (*e.g.* ALH-78006 in Fig. 6) are similar to those in Nagaria (Fig. 5). The Allan Hills-78006 meteorite contains minor diogenitic pyroxene, Juvinas-like pigeonites, and a thermally annealed matrix. The common cumulate eucrite type clasts in Yamato polymict eucrites are generally of the Binda-type. Binda-type pyroxene has been found in Y-74159, Y-74450, Y-75011, Y-75015 and Y-790007 (TAKEDA *et al.*, 1983). It is rare in Allan Hills polymict eucrite specimens (MIYAMOTO *et al.*, 1979; GROSSMAN *et al.*, 1981; DELANEY *et al.*, 1983a, b) and in Elephant Moraine (EETA) specimens (REID and SCORE, 1981; MASON and CLARK, 1982). Allan Hills-78006 is similar to Macibini, as described by REID (1974).

4.1.4. Ordinary eucrites

The non-Antarctic eucrites, excluding cumulate eucrites and Pasamonte, have been called common eucrites or ordinary eucrites in the howardite parent body (TAKEDA, 1979). The bulk compositions of eucrites, when plotted as wt% TiO_2 or Na_2O *vs.* molar Mg/(Mg+Fe), fall into several groups (*e.g.* main group) with some apparent anomalies (BASALTIC VOLCANISM STUDY PROJECT, 1981, p. 229). Stannern and Nuevo Laredo are situated at the ends of two separate compositional trends. It is proposed that they are the products of small degrees of partial melting, or the end products of differentiation (STOLPER, 1977; CONSOLMAGNO and DRAKE, 1977). In most ordinary eucrites, pyroxene compositions lie on a tie line between a calcium-rich and calcium-poor end-member. Variation of Ca content along the tie lines can be attributed to the incomplete resolution of exsolved augite lamellae by EPMA. Because of this feature, REID and BARNARD (1979) described them as equilibrated eucrites.

The high concentrations of Na_2O in Stannern (WOODEN *et al.*, 1981), and in basaltic clasts of the Antarctic polymict eucrites, suggests their possible cogenetic relationship. Nuevo Laredo contains more iron-rich pyroxene than does the main group eucrites, and exhibits a rapidly cooled texture with fine acicular plagioclase. Stannern and Nuevo Laredo have the same type or degree of homogenization of pyroxene.

The clouding observed in eucrites seems to be related to the degree of homogenization of the pyroxenes. Stannern and Nuevo Laredo show considerable clouding. Y-790266 pyroxene, which is partly homogenized, shows minor precipitation of ilmenite. The size of ilmenite platelets is smaller than in Juvinas. The least homogenized pigeonite in Y-75011 does not show any evidence of ilmenite precipitation, but submicroscopic fractures that might act as nucleation sites for ilmenite precipitation are present. Of the many Antarctic eucrites, only monomict eucrites Y-74356 (TAKEDA, 1979) and Reckling Peak (RKPA) 80204 and 80224 exhibit extensive clouding in pyroxenes.

Ibitira is said to be a quickly cooled basalt because of the presence of vesicles, but has the most homogenized eucritic pyroxene with no zoning and augite lamellae up to 5 μm wide are well developed (STEELE and SMITH, 1976). Ibitira also differes from most other eucrites, and from many eucritic clasts as its plagioclase is also homogeneous. Ibitira is the most homogenized of all basaltic achondrites, but has not examined in this study.

4.2. Degree of homogenization of eucritic pyroxenes

REID and BARNARD (1979) characterized equilibrated and unequilibrated eucrites, but a true picture of the homogenization of the chemical zoning is more complex, as noted above. Using the information now available from Antarctic and non-Antarctic chemical trends (Fig. 7), we can arrange the eucritic meteorites into an order of homogenization of pyroxene as follows:

(1) Y-75011: This contains the most extensive Mg-Fe zoning trend in pyroxene and Fe-rich augite; fayalite and probable pyroxferroite are preserved in the mesostasis. Example: clasts in Y-74450 and Y-75015.

(2) Pasamonte: Fe-rich pyroxenes in the Y-75011 trend are not seen and a Mg-Fe-Ca trend is preserved. Example: clasts in Y-74159.

(3) Y-790266: Chemical zoning of Mg-Fe variation has mostly disappeared but a Fe-Ca trend from core to rim is preserved.

(4) Stannern and Nuevo Laredo: The trend from the host to exsolved augite is dominant, but the original Fe-Ca trend can be recognized. Mesostasis becomes more transparent.

(5) Juvinas: All traces of chemical zoning have disappeared and the exsolution trend is dominant. Example: Haraiya, Sioux Co.

(6) Ibitira: This may be added as a provisional type 6, according to STEELE and SMITH (1976), but further study is required to confirm this classification.

The 'degree of homogenization of pyroxene' proposed here may be used in the same sense as that of "petrologic type" of chondrites. Homogenization of feldspar seems unrelated to the effects seen in pyroxene and is rarely seen.

Thermal annealing is proposed for this homogenization for the following reasons (TAKEDA *et al*., 1978): The occurrence of a limited range of Fe/(Fe+Mg) (=0.53–0.63 atomic ratio) in pigeonite of the main group eucrites implies a close approach to internal equilibrium, as could occur in slow cooling (autometamorphism) or in thermal annealing. The basalt fragments of Sioux Co. (coarsest), Juvinas (intermediate) and Nuevo Laredo (finest) span the range of original pyroxene grain size found in Pasamonte and the Antarctic polymict eucrites. The subophitic to variolitic textures of these meteorites imply a range of rapid crystallization rates. This is in agreement with the interpretation of dynamic crystallization experiments of WALKER *et al.* (1978), which suggest that crystallization of Stannern occurred under near surface conditions. Chemical homogenization must have occurred later.

The presence of homogeneous pyroxene with well developed exsolution therefore suggests thermal annealing. MIYAMOTO and TAKEDA (1977) developed a model for the estimation of cooling rates based on the width of augite exsolution lamellae. Cooling rates of $40°/10^4$ to $30°/10^2$ years for exsolution lamellae found in Juvinas pigeonite were calculated. No matter which estimate is more accurate the discrepancy between the slow cooling estimated from the exsolution and the rapid cooling from the textures suggests that these meteorites must have been subjected to extended subsolidus annealing; the observed exsolution effects were not caused by the liquid crystallization event as was argued by TAKEDA *et al.* (1978). The remnant of chemical zoning found in Y-790266 and Stannern indicates that such annealing should also equilibrate Fe/Mg variations in orginally zoned pyroxene grains to produce the zoning patterns in these eucrites.

On the basis of our observations on the eucritic clasts with five different 'degrees of homogenization' of pyroxene, we consider the thermal events in time and space of their parent body. Two lines of evidence must be considered: (1) basalts with the lowest degree of homogenization occur mostly as clasts in polymict breccias, and those with a higher degree occur as a single monomict meteorite, and (2) components of ordinary eucrite type (Juvinas type) in polymict eucrites are uncommon in general, occur mostly as mineral fragments, rather than lithic fragments. They do not show the clouding commonly observed in the non-Antarctic eucrites. These two facts are not obvious but may imply that the material (type 1) excavated from its lava unit by meteorite impacts and incorporated into the parent body regolith could have been protected from a later thermal annealing event. Further study is required to substantiate this idea.

Additional evidence of metamorphism was observed in the Y-7308 breccia (NEHRU *et al*., 1983). Reaction rims of orthopyroxene on silica clasts indicates clast-regolith interaction (FUHRMAN and PAPIKE, 1981). Devitrification of the rims of glass clasts suggests that these clasts were quenched and then injected into a warm regolith. Extensive regolith metamorphism is believed to have homogenized Fe/Mg in Elephant Moraine (EETA) polymict eucrites (DELANEY *et al*., 1982) and the magnesian mafic clasts in Y-7308 must be examined to determine whether they represent metamorphosed-homogenized clasts in a metabreccia. It seems unlikely, however, that Y-7308 shows such pervasive metamorphism, at least in its present state.

4.3. Distribution of terrain units on the HED parent body

The presence of quickly cooled lava-like clasts in polymict eucrites suggests that some parts of the surface of the HED parent body were covered by lava. Survival of large clasts of the lava in the breccia and their round outer shape may be explained by a mechanism in which the base surge of the impact peels off lava units and transports and mixes them into the regolith. The rounded shapes of clasts may be evidence of this process (KING, personal commun., 1978).

At the base of a thick lava unit or a layered intrusion, ordinary eucrites and cumulate eucrites may be produced, and exsolution of pyroxenes may be developed. It is generally understood that deeper materials can be excavated by a jetting mechanism. Only fine fragments of these materials may be supplied to the regolith because of crushing by this mechanism. We estimate that the thickness of this layer may be thinner than that postulated by the layered crust model (TAKEDA, 1979), as evidenced by the population of such material in polymict eucrites.

Fractured rocks and monomict eucrites left at the base of the impact crater or around the crater, and the fractured lava units covered by regolith, then experienced extended subsolidus annealing events and were partly or totally homogenized. A part of the regolith may also have been reheated by a later impact event or events. The high temperature reheatnig or prolonged low temperature annealing events may be analogous to the stage of lunar evolution that produced extensive lunar mare basalts or to a later impact heating. If the HED parent body was small, then internal temperatures could not rise high enough to produce a second generation of basaltic volcanism as in the case of lunar mare basalts.

The presence of only Binda-type cumulate eucrites in the Yamato polymict eucrites indicates that there are local differences or lateral heterogeneity in the cumulate type, or that there may be two type of cumulate eucrites that are not genetically related. Cumulate eucrites rich in modal plagioclase such as Moore County, Serra de Magé and Moama may be genetically distinct from Binda-type cumulate eucrites as was mentioned by NEHRU *et al.* (1980). Plagioclase-rich cumulate eucrites may be remote from the Yamato polymict eucrite sites. If we simply apply the lunar crust formation model, plagioclase-rich cumulate eucrites may be analogous to early formed lunar crust type terrain, but we do not have any clear evidence to support this idea.

The association of cumulate eucrites with diogenites in the 1979 Yamato meteorite collection (TAKEDA and YANAI, 1982) and in non-Antarctic diogenites (HEWINS, 1983), suggests that cumulate eucrite-like rocks can be derived from magma that produced diogenites. The high abundance of rare earths in Y-75032 (SHIMIZU and MASUDA, 1981), which is a diogenite-like plagioclase-poor cumulate eucrite, implies that it can be a product from diogenitic magma.

The absence of lava-like eucrites having compositions like Y-75032, which were produced by large scale partial melting, in meteorite collections or as clasts in polymict eucrites suggests that such liquids never extruded on the surface of the HED parent body. Large scale partial melting of the residues of the previous partial melting responsible for eucritic lavas (STOLPER, 1977) could lead to the production of cumulate diogenite and residual material similar to cumulate eucrites. The final residue of the above melting may be volumetrically small and consist of olivine, depending on the original bulk composition of the source region. The second stage melting of diogenite may be related to the second high temperature metamorphic event that homogenized many ordinary eucrites. Further work is required to refine this model.

Fractionation of cumulate diogenite has been proposed on the basis of the Y-7308 howardite (NEHRU *et al.*, 1983). This breccia, and other basaltic achondrites, sample compositionally continuous suites of basalts and gabbros; these range from diogenites to magnesian basalts and gabbros to the iron-rich monomict eucrites. It seems unlikely that the partial melt model for eucrites (STOLPER, 1977) can be extended to these magnesian compositions. In particular, the augite-rich basalts in Y-7308 (NEHRU *et al.*, 1983) are unlikely to be partial melts from the same source composition as the eucrites. The composition of the source of these basalts probably lies above the Opx-Plag alkemade line in the Ol-An-SiO_2 pseudoternary of STOLPER (1977) and their genesis probably involved fractionation of a cumulate orthopyroxenite suite.

The terrain model postulated above is consistent with a surface model of Vesta proposed by GAFFEY (1983), on the basis of his observational rotational studies of reflectance spectra. The dark eucritic terrain may correspond to the mesostasis rich surface eucrites with a lower degree of homogenization. The diogenite-rich terrain may have been exposed by larger impacts that excavated materials down to the diogenite layer (TAKEDA, 1979) and produced the howardite breccias. Much deeper excavation by still larger impacts may expose materials below the diogenite layer.

In summary, the parent body of the HED meteorite has been postulated by combining information obtained both on Antarctic and non-Antarctic HED meteorites. Each one of these groups of meteorites samples closely related but separate sites on the parent body. Five different degrees of homogenization of eucrites can be correlated with the different stages and locations of events, including lava extrusions, impact excavation, and thermal annealing events.

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References

BASALTIC VOLCANISM STUDY PROJECT (1981): Basaltic Volcanism on the Terrestrial Planet. New York, Pergamon, 1286 p.

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.

DELANEY, J. S., PRINZ, M., NEHRU, C. E. and O'NEILL, C. (1982): The polymict eucrites Elephant Moraine A79004 and A79011 and the regolith history of a basaltic achondrite parent body. Proc. Lunar Planet. Sci. Conf. 13th, Pt. 1, A339–A352 (J. Geophys. Res., **87**, Suppl.).

DELANEY, J. S., PRINZ, M., HARLOW, G. F. and NEHRU, C. E. (1983a): The petrography of the polymict eucrite Allan Hills A78040. Geochim. Cosmochim. Acta, **47** (in press).

DELANEY, J. S., PRINZ M. and TAKEDA, H. (1983b): The polymict eucrites. Lunar and Planetary Science XIV. Houston, Lunar Planet. Inst., 152–153.

DELANEY, J. S., TAKEDA, H., PRINZ, M., NEHRU, C.E. and HARLOW, G. E. (1983c): The nomenclature of polymict basaltic achondrites. Meteoritics, **18**, 103–111.

DUKE, M. B. and SILVER, L. T. (1967): Petrology of eucrites, howardites and mesosiderites. Geochim. Cosmochim. Acta, **31**, 1637–1665.

FITZGERALD, M. J. (1980): Muckera and Millbillillie-Australian achondritic meteorites. Trans. R. Soc. South Aust., **104** (Pt. 6), 201–209.

FUHRMAN, M. and PAPIKE, J. J. (1981): Howardites and polymict eucrites; Regolith samples from the eucrite parent body. Petrology of Bholgati, Bununu, Kapoeta and ALHA76005. Proc. Lunar Planet. Sci. Conf. 12B, 1257–1280.

GAFFEY, M. J. (1983): The Asteroid (4) Vesta; Rotational spectral variations, surface material heterogeneity, and implications for the origin of the basaltic achondrites (abstract). Lunar and Planetary Science XIV. Houston, Lunar Planet. Inst., 231–232.

GOODING, J. L., PRINZ, M. and KEIL, K. (1979): Mineralogy and petrology of the Chervony Kut eucrite (abstract). Lunar and Planetary Science X. Houston, Lunar Planet. Inst., 446–449.

GROSSMAN, L., OLSEN, E., DAVIS, A. M., TANAKA, T. and MACPHERSON, G. J. (1981): The Antarctic achondrite ALHA76005; A polymict eucrite. Geochim. Cosmochim. Acta, **45**, 1267–1279.

HARLOW, G. E. and KLIMENDITIS, R. (1980): Clouding of pyroxenes and plagioclase in eucrites; Implications for post-crystallization processing. Proc. Lunar Planet. Sci. Conf. 11th, 1131–1148.

HARLOW, G. E., NEHRU, C. E., PRINZ, M., TAYLOR, G. J. and KEIL, K. (1979): Pyroxenes in Serra de Magé; Cooling history in comparison with Moama and Moore County. Earth Planet. Sci. Lett., **43**, 173–181.

HESS, H. H. and HENDERSON, E. P. (1949): The Moore County meteorite; A further study with comment on its primordial environment. Am. Mineral., **34**, 494–507.

HEWINS, R. H. (1983): Diogenites and related magmas. Lunar and Planetary Science XIV. Houston, Lunar Planet. Inst., 309–310.

ISHII, T. and TAKEDA, H. (1974): Inversion, decomposition and exsolution phenomena of terrestrial and extraterrestrial pigeonites. Mem. Geol. Soc. Japan, **11**, 19–36.

LABOTKA, T. C. and PAPIKE, J. J. (1980): Howardites; Samples of the regolith of the eucrite parent body: Petrology of Frankfort, Pavlovka, Yurtuk, Malvern, and ALHA77302. Proc. Lunar Planet. Sci. Conf. 11th, 1103–1130.

LINDSLEY, D. H. and ANDERSON, D. J. (1983): A two-pyroxene thermometer. Proc. Lunar Planet. Sci. Conf. 13th, Pt. 2, A887–A906 (J. Geophys. Res., **88**, Suppl.).

LINDSLEY, D. H. and MUNOZ, J. L. (1969): Subsolidus relations along the join hedenbergite-ferrosilite. Am. J. Sci., **267A**, 295–324.

MASON, B. and CLARK, R. S. (1982): Characterization of the 1980–81 Victoria Land meteorite collections. Mem. Natl Inst. Polar Res., Spec. Issue, **25**, 17–33.

MASON, B., JAROSEWICH, E. and NELEN, J. A. (1979): The pyroxene-plagioclase achondrites. Smithson. Contrib. Earth Sci., **22**, 27–45.

MIYAMOTO, M. and TAKEDA, H. (1977): Evaluation of a crust model of eucrites from the width of exsolution lamellae. Geochem. J., **11**, 161–169.

MIYAMOTO, M., TAKEDA, H., YANAI, K. and HARAMURA, H. (1979): Mineralogical examination of the Allan Hills No. 5 meteorite. Mem. Natl Inst. Polar Res., Spec. Issue, **12**, 59–71.

MORI, H. and TAKEDA, H. (1981a): Evolution of the Moore County pyroxenes as viewed by an analytical transmission electron microscope (ATEM) (abstract). Meteoritics, **16**, 362–363.

MORI, H. and TAKEDA, H. (1981b): Thermal and deformational histories of diogenites as inferred from their microtextures of orthopyroxenes. Earth Planet. Sci. Lett., **53**, 266–274.

MORI, H. and TAKEDA, H. (1982): Analytical electron microscopic studies of pigeonites in eucrites. Papers presented to the Seventh Symposium on Antarctic Meteorites, 19–20 February 1982. Tokyo, Natl Inst. Polar Res., 26–28.

NAKAMURA, Y. and KUSHIRO, I. (1970): Compositional relations of coexisting orthopyroxene, pigeonite and augite in a tholeiitic andesite from Hakone volcano. Contrib. Mineral. Petrol., **26**, 265–275.

NEHRU, C. E., DELANEY, J. S., HARLOW, G. E. and PRINZ, M. (1980): Mesosiderite basalts and the eucrites (abstract). Meteoritics, **15**, 337–338.

NEHRU, C. E., DELANEY, J. S., PRINZ, M., WEISBERG, M. and TAKEDA, H. (1983): Yamato-7308, an important howardite. Lunar and Planetary Science XIV. Houston, Lunar Planet. Inst., 550–551.

POWELL, M. A., WALKER, D. and HAYS, J. F. (1980): Controlled cooling and crystallization of a eucrite; Microprobe studies. Proc. Lunar Planet. Sci. Conf. 11th, 1153–1168.

PRINZ, M., NEHRU, C. E., DELANEY, J. S., HARLOW, G. E. and BEDELL, R. L. (1980): Modal studies of mesosiderites and related achondrites, including the new mesosiderite ALHA77219. Proc. Lunar Planet. Sci. Conf. 11th, 1055–1071.

REID, A. M. (1974): The Macibini meteorite and some thoughts on the origin of basaltic achondrites (abstract). Meteoritics, **9**, 398–399.

REID, A. M. (1982): Overview of Antarctic achondrites. Smithson. Contrib. Earth Sci., **24**, 59–64.

REID, A. M. and BARNARD, B. M. (1979): Unequilibrated and eqilibrated eucrites. Lunar and Planetary Science X. Houston, Lunar Planet. Inst., 1019–1022.

REID, A. M. and SCORE, R. (1981): A preliminary report on the achondrite meteorites in the 1979 U.S. Antarctic meteorite collection. Mem. Natl Inst. Polar Res., Spec. Issue, **20**, 33–52.

SIMON, S. B., PAPIKE, J. J. and FUHRMAN, M. (1982): Petrology of EETA79006 and implications for the formation of polymict eucrites. Meteoritics, **17**, 149–162.

SHIMIZU, H. and MASUDA, A. (1981): REE, Ba, Sr and Rb abundances in some unique Antarctic achondrites. Mem. Natl Inst. Polar Res., Spec. Issue, **20**, 211–220.

SHIMIZU, H. and MASUDA, A. (1982): REE characteristics of Antarctic eucrites. Mem. Natl Inst. Polar Res., Spec. Issue, **25**, 145–152.

STEELE, I. M. and SMITH, J. V. (1976): Mineralogy of the Ibitira eucrite and comparison with other eucrites and lunar samples. Earth Planet. Sci. Lett., **33**, 67–78.

STOLPER, E. (1977): Experimental petrology of eucritic meteorites. Geochim. Cosmochim. Acta, **41**, 587–611.

TAKEDA, H. (1979): A layered crust model of a howardite parent body. Icarus, **40**, 455–470.

TAKEDA, H. and YANAI, K. (1982): Mineralogical examination of the Yamato-79 achondrites; Polymict eucrites and ureilites. Mem. Natl Inst. Polar Res., Spec. Issue, **25**, 97–123.

TAKEDA, H., MIYAMOTO, M. and DUKE, M. B. (1976a): Pasamonte pyroxenes, a eucritic analogue of lunar pyroxenes. Meteoritics, **11**, 372–374.

TAKEDA, H., MIYAMOTO, M., ISHII, T. and REID, A. (1976b): Characterization of crust formation on a parent body of achondrites and the moon by pyroxene crystallography and chemistry. Proc. Lunar Sci. Conf. 7th, 3535–3548.

TAKEDA, H., MIYAMOTO, M., DUKE, M. B. and ISHII, T. (1978): Crystallization of pyroxenes in lunar KREEP basalt 15386 and meteoritic basalts. Proc. Lunar Planet. Sci. Conf. 9th, 1157–1171.

TAKEDA, H., MIYAMOTO, M., ISHII, T., YANAI, K. and MATSUMOTO, Y. (1979): Mineralogical examination of the Yamato-75 achondrites and their layered crust model. Mem. Natl Inst. Polar Res., Spec. Issue, **12**, 82–108.

TAKEDA, H., MORI, H., YANAI, K. and SHIRAISHI, K. (1980): Mineralogical examination of the Allan Hills achondrites and their bearing on the parent bodies. Mem. Natl Inst. Polar Res., Spec. Issue, **17**, 119–144.

TAKEDA, H., MORI, H. and YANAI, K. (1981a): Mineralogy of the Yamato diogenites as possible pieces of a single fall. Mem. Natl Inst. Polar Res., Spec. Issue, **20**, 81–99.

TAKEDA, H., MORI, M., ISHII, T. and MIYAMOTO, M. (1981b): Thermal and impact histories of pyroxenes in lunar eucrite-like gabbros and eucrites. Proc. Lunar Planet. Sci. Conf. 12B, 1297–1313.

TAKEDA, H., WOODEN, J. L., MORI, H., DELANEY, J. S., PRINZ, M. and NYQUIST, L. E. (1983): Comparison of Yamato and Victoria Land polymict eucrites; A view from mineralogical and isotopic studies. Proc. Lunar Planet. Sci. Conf. 14th, Pt. 1, B245–B256 (J. Geophys. Res., **88**, Suppl.).

WALKER, D., POWELL, M. A., LOFGREN, G. E. and HAYS, J. F. (1978): Dynamic crystallization of a eucritic basalt. Proc. Lunar Planet. Sci. Conf. 9th, 1369–1391.

WOODEN, J., REID, A. M., BROWN, R., BANSAL, B., WIESMANN, H. and NYQUIST, L. (1981): Chemical and isotopic studies of the Allan Hills polymict eucrites. Lunar and Planetary Science XII. Houston, Lunar Planet. Inst., 1203–1205.

WOODEN, J. L., TAKEDA, H., NYQUIST, L. E., WIESMANN, H. and BANSAL, B. (1983): A Sr and Nd isotopic study of five Yamato polymict eucrites and a comparison to other Antarctic and ordinary eucrites. Mem. Natl Inst. Polar Res., Spec. Issue, **30**, 315–322.

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