MINERALOGICAL EXAMINATION OF THE ALLAN HILLS NO. 5 METEORITE

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***Abstract*:** Electron microprobe studies have been made of pyroxenes from the Allan Hills No. 5 meteorite. This meteorite shows the brecciated texture and was identified as 'eucritic polymict breccia'. Representative pyroxenes in this meteorite can be classified into four groups: (A) Pyroxenes which have a chemically uniform core with a Fe-rich rim. (B) Pyroxenes which show both the Mg–Fe chemical zoning and the exsolution texture. (C) Pyroxene which consists of a portion which has a uniform core with a Fe-rich rim like Type (A) and another portion which shows the exsolution texture and the Mg–Fe chemical zoning like Type (B) within a single grain. (D) Juvinas-like pyroxenes which show the fine exsolution texture with the uniform chemical composition. By the discovery of these pyroxenes in this meteorite, it was proved that the pyroxenes contained in eucritic polymict breccias have a close genetic relationship. Based on the mineralogical examination of these pyroxenes and the surface brecciation process of our proposed layered crust model for an achondrite parent body, we suggested that the eucritic polymict breccia is a good candidate for its surface material.

1. Introduction

Extensive studies of achondrites have been impeted by the limited number and variety of achondrites. By the epoch-making discovery of many meteorites (including ten-odd achondrites) in Antarctica, especially in the Yamato Mountains range (NAGATA, 1975; YOSHIDA *et al.*, 1971; KUSUNOKI, 1975; SHIRAISHI *et al.*, 1976;

YANAI, 1976, 1977, 1978a; YANAI *et al.*, 1976; MATSUMOTO, 1977, 1978), the difficulty due to the scarcity of achondrites has been overcome.

Common achondrites, such as eucrites, howardites and diogenites, have been considered to be lithified brecciated debris on the surface layer of a small parent body (achondrite parent body) (DUKE and SILVER, 1967; BUNCH, 1975). Polymict breccias of eucrite composition, Yamato-74159 and -75011 found among the Yamato meteorites, have supplied important information on the brecciation processes on the surface of an achondrite parent body (MIYAMOTO *et al.*, 1978b). Namely, these 'eucritic polymict breccias' may be a good candidate for the surface materials of a Vesta-like asteroid (LEBERTRE and ZELLNER, 1978). Thus, the preliminary examinations of the Yamato achondrites (TAKEDA *et al.*, 1978b) have brought the important results on the processes of crust formation and brecciation of an achondrite parent body, and by these results the comparative planetology between our moon and an achondrite parent body about the crust formation and brecciation processes has been developed (TAKEDA and MIYAMOTO, 1977; TAKEDA *et al.*, 1978a; MATSON *et al.*, 1976).

In this paper, we will report a mineralogical examination of a newly found achondrite (YANAI, 1978b), Allan Hills No. 5, collected by a U.S.–Japan joint party in Antarctica in 1977. Based on our crust model of an achondrite parent body (TAKEDA *et al.*, 1976b), we will interpret the surface brecciation process of the proposed parent body of the meteorite.

2. Samples and Experimental Technique

The Allan Hills No. 5 meteorite was found in the bare ice area on the plateau side of Allan Nunatak on January 20, 1977 by a U.S.–Japan joint party of "Antarctic Search for Meteorites" (YANAI, 1978b). The original meteorite was 1425 g in weight and was tentatively identified as achondrite (howardite) (YANAI, 1978b). The piece supplied from the National Institute of Polar Research is $6.0\times10.5\times4.5$ mm in size. One side of the piece is a cut surface of the original meteorite, on which a few white clasts about 1 mm in diameter (plagioclases) and much smaller dark brown mineral fragments (pigeonites) are seen in hand specimen. Two-thirds of the piece was cut and mounted in epoxy and the rest was preserved for the spectroscopic investigation.

Two slices (slice Nos. 1 and 2), each 0.15 mm thick, were cut from the above rock fragment mounted in epoxy resin. For microprobe analysis we prepared the polished thin section (No. 2) cemented by Araldite and the polished thick (about 0.08 mm thick) section (No. 1) cemented by Lakeside 70 for easy removal of single crystals for the subsequent single crystal X-ray diffraction studies. The detailed sample preparation technique is the same as that described by TAKEDA *et al.* (1978b) and MIYAMOTO *et al.* (1978b).

The quantitative chemical analysis of pyroxenes were made with a Japan Electron Optics Laboratory Co. JXA-5 electron probe X-ray microanalyzer with a 40° take off angle. The method was the same as that described by NAKAMURA and KUSHIRO (1970).

The electron probe traverses were performed by monitoring Mg Kα, Fe Kα and Ca Kα radiations across the pyroxene crystals. The width of augite lamellae in pigeonites was measured on the scan charts. If the direction of the augite lamellae is not perpendicular to that of the track of electron probe, the width of augite lamellae is multiplied by the cosine of the angle between two directions.

3. Results

The Allan Hills No. 5 meteorite is a breccia which contains variety of pyroxene and calcic plagioclase fragments in fine-grained matrix (Fig. 1). In this section (No. 2), fine-grained ophitic clast (about 1 mm in diameter) is present, which is texturally similar to that found in eucritic polymict breccias, Yamato-74159 and -75011 (MIYAMOTO *et al.*, 1978b; TAKEDA *et al.*, 1978a, b). The meteorite is clearly polymict in terms of lithic variability, but carries no magnesian orthopyroxene of the type found in howardites.

On the basis of the chemical composition and the exsolution texture, representative pyroxene grains in the Allan Hills No. 5 can be grouped into four types:

(A): Pyroxene grains which have a chemically uniform core ($Mg_{61}Fe_{33}Ca_6$, average) with a Fe-rich rim whose composition comes to $Mg_{37}Fe_{59}Ca_4$ (average; Fig. 2). One large pyroxene crystal (grain No. 35), about 1 mm in diameter, has a uniform core ($Mg_{63}Fe_{32}Ca_5$) with a Fe-rich thin (about 30 micron) rim of

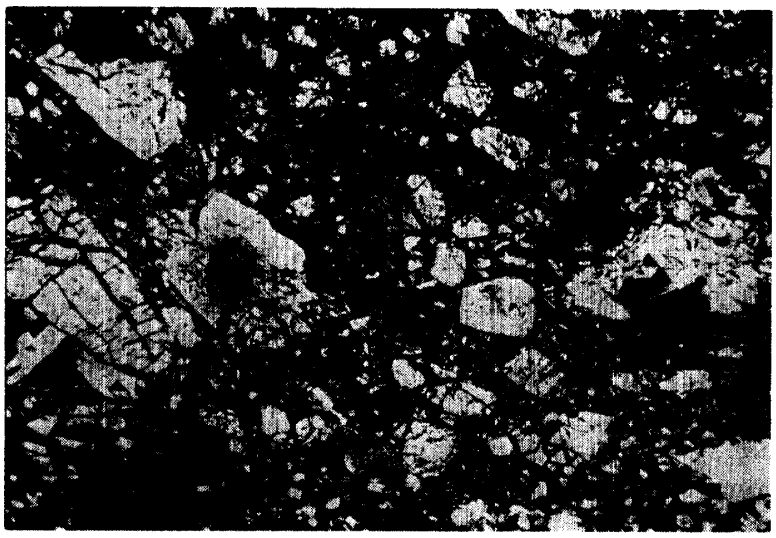

Fig. 1. Photograph of thin section (No. 2) of Allan Hills No. 5. Width is 3 mm.

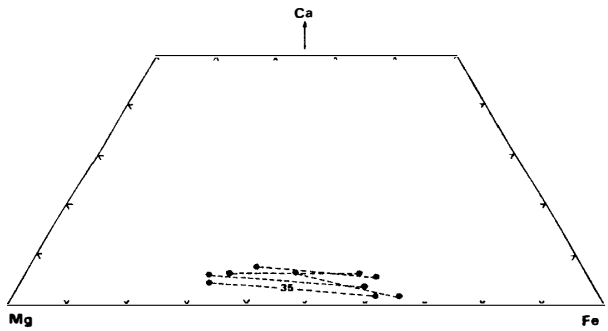

Fig. 2. Compositions of Type (A) pyroxenes in Allan Hills No. 5. Dotted lines indicate the range of the Mg–Fe chemical zoning. 35: grain No. 35.

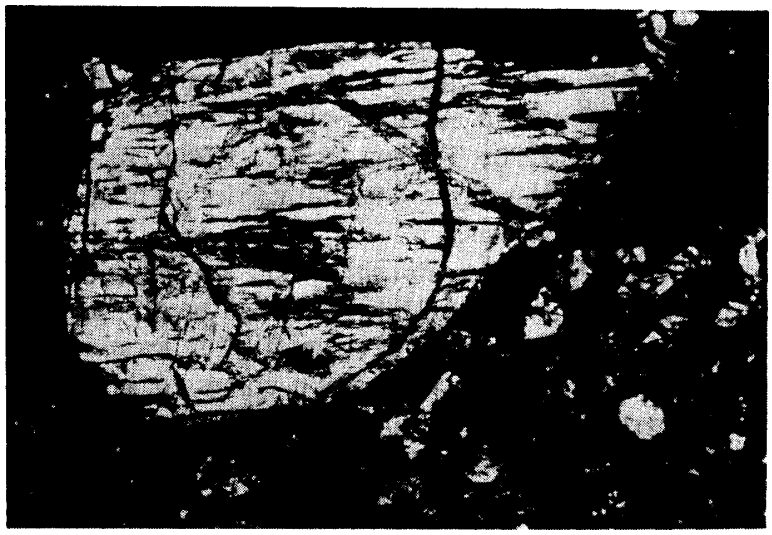

Fig. 3. Photograph of grain No. 35. Width is 1 mm.

$Mg_{37}Fe_{61}Ca_2$ (Fig. 3).

(B): Pyroxene grains which show the Mg–Fe chemical zoning and the exsolution texture such as grains No. 9 and No. 6 (Fig. 4; Fig. 5). The Mg/(Mg+Fe) ratio of core of these grains ($Mg_{48}Fe_{42}Ca_{10}$) is similar to that of pyroxene from the Moore County meteorite ($Mg_{46}Fe_{44}Ca_{10}$). The width of exsolution lamellae is 5 microns in both grains No. 9 and No. 6.

(C): Pyroxene grain No. 22 (Fig. 6; Fig. 7). This grain is a unique crystal and is divided into two portions as follows: (1) A portion which has a uniform Mg-rich core ($Mg_{46}Fe_{49}Ca_5$) with a Fe-rich thin rim ($Mg_{39}Fe_{59}Ca_2$) such as Type (A) pyroxene (grain No. 35). This portion covers three quarters of the grain. (2) Another portion which shows the exsolution texture and the Mg–Fe chemical zoning as was observed in Type (B) pyroxene. The exsolution texture in portion (2) is apparently similar to Juvinas pyroxene and the width of exsolution lamellae is

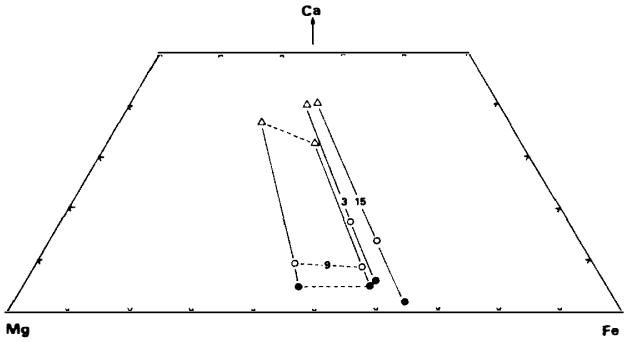

Fig. 4. Compositions of Types (B) and (D) pyroxenes in Allan Hills No. 5. Dotted lines indicate the range of the Mg–Fe chemical zoning. Numbers on lines indicate grain No. The lines indicate coexisting host-lamellae pair. Open circles: bulk composition.

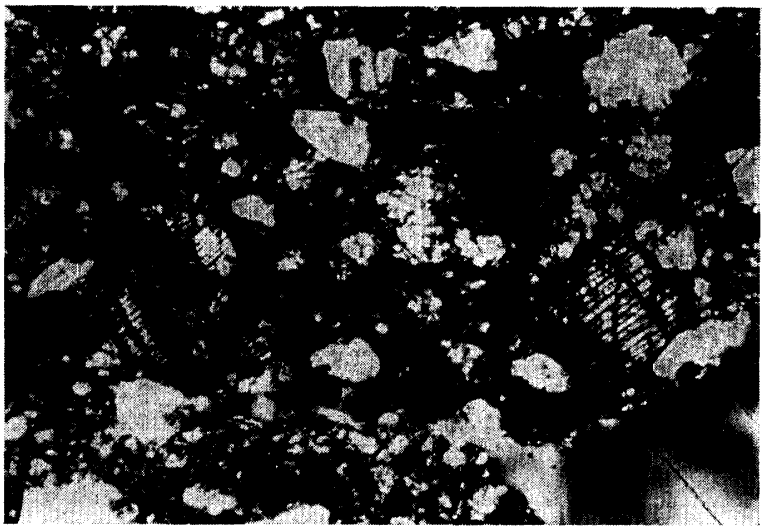

Fig. 5a. Photograph of grain No. 9. Width is 1 mm.

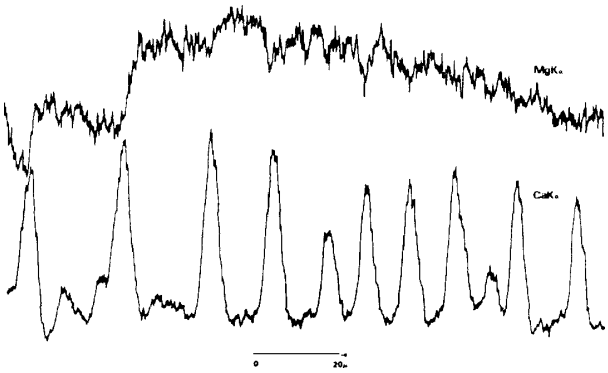

Fig. 5b. Analytical traverse of grain No. 9 (an arrow).

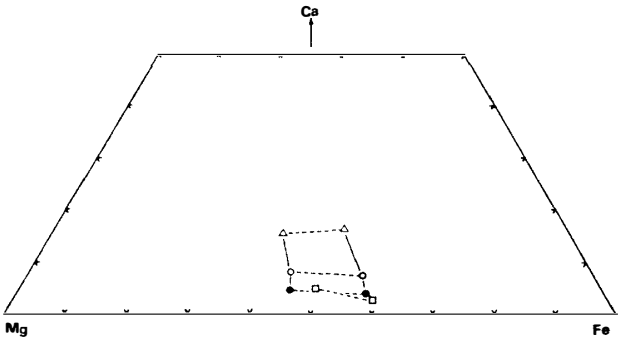

Fig. 6. Compositions of Type (C) pyroxene (grain No. 22). Dotted lines indicate the range of the Mg–Fe chemical zoning. The lines indicate coexisting host-lamellae pair. Open circles: bulk composition. Squares: Compositions of portion (1). Others: Compositions of portion (2).

Fig. 7a. Photograph of grain No. 22. Width is 1 mm.

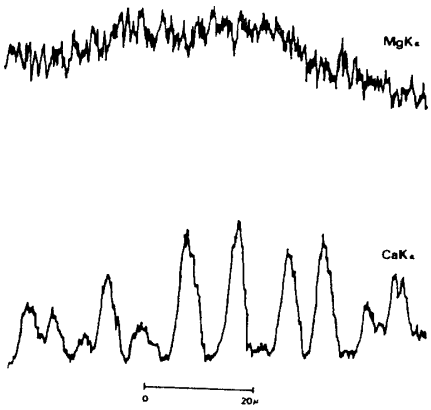

Fig. 7b. Analytical traverse of portion (2) of grain No. 22 (an arrow).

about 7 microns. However, the salient difference from Juvinas pyroxene is the Mg–Fe chemical zoning in portion (2). The ranges of the Mg/(Mg+Fe) ratio of the Mg–Fe chemical zoning of the two portions are almost identical.

(D): Juvinas-like pyroxenes which show the fine exsolution texture with the uniform chemical composition such as grain Nos. 3 and 15 (Fig. 4; TAKEDA *et al.*, 1974a, b). The widths of exsolution lamellae of grain Nos. 3 and 15 are 6.5 and 5.7 microns respectively. The Mg/(Mg+Fe) ratio of grain No. 3 ($Mg_{36}Fe_{47}Ca_{17}$) is similar to Juvinas ($Mg_{36}Fe_{56}Ca_{8}$).

The bulk chemical composition of Type (B) pyroxene is more Mg-rich than that of Type (D) pyroxene, whereas the widths of exsolution lamellae of both pyroxenes are almost identical.

Namely, although the difference in the widths of the exsolution lamellae is small between Types (B) and (D), there is a large difference in major element chemistry.

Pyroxene crystals embeded in the fine-grained ophitic clast show Mg–Fe–Ca compositional variations found in a similar clast in Pasamonte (TAKEDA *et al.*, 1976a) and Yamato-74159 (MIYAMOTO *et al.*, 1978a; TAKEDA *et al.*, 1978a, b). This clast is, however, too fine-grained to examine the details of the Mg–Fe–Ca compositional variation by the electron microprobe. The chemical analyses of the representative pyroxene crystals in this meteorite are shown in Table 1.

Table 1. Representative electron microprobe analyses of pyroxenes (wt. %) from Allan Hills No. 5.

Sample	No. 3			No. 9			No. 22		No. 35
	Host	Pig*	Aug	Host	Pig*	Aug	Host	Pig*	Core
SiO_2	47.71	48.64	50.11	49.66	49.79	49.77	49.11	49.28	51.65
Al_2O_3	0.79	1.19	1.85	0.60	0.87	2.21	1.05	1.03	1.09
TiO_2	0.26	0.43	0.62	0.47	0.60	1.06	0.13	0.41	0.16
Cr_2O_3	0.30	0.53	0.64	0.25	0.35	0.49	0.56	0.49	0.88
FeO	33.16	27.33	16.92	29.05	27.10	19.80	30.37	29.25	19.61
MnO	0.97	0.84	0.50	0.84	0.74	0.39	0.84	0.92	0.64
MgO	12.73	11.72	10.61	16.58	15.95	14.56	15.48	15.12	23.26
CaO	2.40	7.77	18.62	2.31	4.52	11.57	2.18	3.63	2.58
Na_2O	0.03	0.05	0.10	0.02	0.00	0.01	0.06	0.00	0.00
Total	98.35	98.50	99.97	99.78	99.92	99.86	99.78	100.13	99.87
Ca**	5.2	17.1	40.0	4.8	9.4	24.5	4.6	7.6	5.1
Mg	38.5	35.9	31.7	48.0	46.4	42.8	45.4	44.3	64.4
Fe	56.3	47.0	28.3	47.2	44.2	32.7	50.0	48.1	30.5

* Bulk composition including exsolved phase.
** Mole percent.

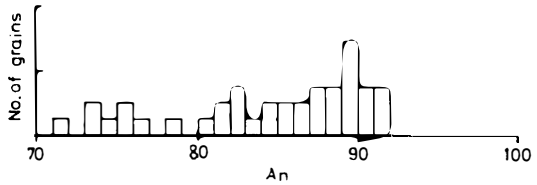

Fig. 8. Histogram of plagioclase compositions, expressed as mole % anorthite.

Table 2. Bulk composition of Allan Hills No. 5.

SiO_2	48.21	$H_2O(-)$	0.27
TiO_2	0.78	$H_2O(+)$*	1.1
Al_2O_3	12.02	P_2O_5	0.10
FeO	18.89	Cr_2O_3	0.40
MnO	0.52	NiO	0.011
MgO	7.66	FeS	0.17
CaO	9.08	CO	<0.003
Na_2O	0.56		
K_2O	0.06	Total	99.83

Analysis by H. HARAMURA.
* Including volatile components released up to 1100°C.

Plagioclases in this meteorite are calcic members common in eucrite (Fig. 8).

The bulk chemical composition of this meteorite obtained by the standard wet chemical method is shown in Table 2.

4. Discussion

We have been emphasizing the eucritic polymict breccias as possible surface materials of an achondrite parent body or bodies (MIYAMOTO *et al.*, 1977; MIYAMOTO *et al.*, 1978a, b). In Yamato-74159, a polymict breccia with a eucritic bulk composition, there were found pyroxenes and lithic fragments of various known eucrites. The coexistence of the Pasamonte-like pyroxenes with the chemical zoning and the Juvinas-like pyroxenes with the uniform chemical composition and exsolution is worthy of note. However, the genetic relationship between the two types of eucritic pyroxene has not been elucidated. The Allan Hills No. 5 pyroxenes are similar to those of the above meteorites, but there are found more variety of pyroxenes between the above two types. Especially, the pyroxenes with both chemical zoning like Pasamonte and exsolution texture like Juvinas are found within a single grain.

Type (A) pyroxenes which have a Mg-rich core and a Fe-rich thin rim have been already found in eucritic polymict breccias (MIYAMOTO *et al.*, 1978b; TAKEDA

et al., 1976a, 1978a). The most Fe-rich compositions (rim) of Type (A) are almost identical in all grains, whereas the most magnesian compositions (core) are different (Fig. 2). This implies a close genetic relationship among these pyroxenes. The zoning trend of Type (A) pyroxenes is similar to that of pyroxenes surrounded by the plagioclase crystals in the ophitic clasts in Pasamonte (TAKEDA *et al.*, 1976a). Type (A) pyroxenes may be broken fragments of a clast with the Pasamonte-like ophitic texture. Type (A) pyroxenes indicate a rapid cooling history.

Although the Mg/(Mg+Fe) ratio of the core of Type (B) pyroxenes is similar to that of Moore County (Fig. 4), it appears that Type (B) is not of a cumulate origin because of its thin lamellae (about 5 microns) and Mg–Fe chemical zoning. The pyroxene crystal in Moore County has wide exsolution lamellae (about 55 microns) and are partially inverted to orthopyroxene (ISHII and TAKEDA, 1974) and does not show Mg–Fe chemical zoning. The Moore County meteorite has been understood to be crystal cummulate separated from the primary magma at an early stage (TAKEDA *et al.*, 1976b), and may have experienced very slow cooling (about $1.5°C/10^4$ year; MIYAMOTO and TAKEDA, 1977), namely this achondrite may have been located at a deep place in a parent body (about 9.0 km from the surface). In contrast with these results, based on the estimation of absolute cooling rate from the width of exsolution lamellae, the absolute cooling rate of Type (B) pyroxenes is about $5°C/10^2$ year and they may have been located at about 0.8 km under the surface of a parent body.

Type (D) pyroxenes scarcely shows Mg–Fe chemical zoning, and the widths of their exsolution lamellae are about 7 microns similar to that of Juvinas pyroxene (TAKEDA *et al.*, 1974a, b). In the exsolution texture and the Mg/(Mg+Fe) ratio, there is no distinction between Type (D) pyroxene in the Allan Hills No. 5 and the Juvinas pyroxene. The bulk CaO content of Type (D) (about 7.8%) is higher than that of Juvinas (about 3.7%).

Type (C) pyroxene provides an important clue for elucidating the genetic relationship between Types (A) and (B) pyroxenes. In Type (C) pyroxene, regardless of the exsolution texture, the ranges of the Mg–Fe chemical zoning are almost identical between portions (1) and (2). One of the differences between the two portions is that the bulk CaO content of portion (2) (about 3.6%) is higher than that of portion (1) (about 2.2%). This evidence is consistent with the fact that portion (2) shows the exsolution texture.

The pyroxene which shows the Mg–Fe chemical zoning and the pyroxene which shows the exsolution texture have been already found as separate fragments in eucritic polymict breccias (MIYAMOTO *et al.*, 1978b; TAKEDA *et al.*, 1978a, b). The pyroxenes which show the Mg–Fe chemical zoning and the exsolution texture in the same grain such as Type (B) were found in Allan Hills No. 5. Moreover, Type (C) pyroxene consists of Type (A)-like portion (portion (1)) which shows the Mg–Fe chemical zoning only, and Type (B)-like portion (portion (2)) which shows

both the Mg–Fe chemical zoning and the exsolution texture. This fact is a strong evidence of a close genetic relationship of the Type (A) and Type (B) pyroxenes.

One of the differences between Type (A) and Type (B) is that Type (B) pyroxene shows the exsolution texture. It appears that presence of the exsolution texture depends mainly on the CaO content of the grain. In fact, portion (2) of Type (C) has higher CaO content than that of portion (1) and shows the exsolution texture, whereas portion (1) does not show the exsolution texture. If the pyroxene crystallizes rapidly in contact with plagioclases, the pyroxene shows the Mg–Fe chemical zoning without the exsolution texture, because Ca atoms in melt is mostly contained in plagioclases as was observed in pyroxenes in ophitic clasts (MIYAMOTO *et al.*, 1978a; TAKEDA *et al.*, 1978a).

Another difference between Types (A) and (B) is that the most magnesian composition (core) of Type (A) is more Mg-rich than that of Type (B) (Figs. 2 and 4). This may depend on the cooling history of these two types. Namely, Type (A) pyroxene may have experienced a more rapid cooling history than Type (B). This fact is also consistent with that the Type (B) pyroxene shows the exsolution texture.

Although the most magnesian compositions (core) are different among Types (A), (B) and (C), the most Fe-rich compositions (rim) are almost identical to that of Type (D) which is a common eucritic pyroxene such as Juvinas (STOLPER, 1977). This fact may suggest that Types (A), (B), (C) and (D) pyroxene crystals crystallized from a common melt.

WALKER *et al.* (1978) have carried out dynamic crystallization experiments of eucritic composition. They stated that all the textures observed for eucrites can be produced experimentally from the starting materials of the eucritic composition. However, they could not reproduce Juvinas-like pyroxenes with a uniform chemical composition.

The most magnesian composition of pyroxene formed by WALKER *et al.*'s experiment is almost identical to that of Type (A) which may have experienced a rapid cooling history. This implies that the rapidly cooled pyroxenes which show the Mg–Fe chemical zoning such as Types (A), (B) and (C) have crystallized from the melt almost similar to common eucritic composition.

The range of the Mg/(Mg+Fe) ratio of chemical zoning is different among Types (A), (B) and (C) (Figs. 2, 4 and 6). As mentioned above, the most magnesian composition (core) of the pyroxene grain may depend on the cooling history. Namely, the more rapidly it cools, the more magnesian composition the core has. If it cools slowly, the core composition becomes Fe-rich gradually, and the Mg–Fe chemical zoning will disappear. Juvinas-like pyroxene (Type (D)) which does not show the Mg–Fe chemical zoning is one of examples of such slowly cooled grain. It appears that Juvinas-like pyroxene is not the product by the

thermal metamorphism of the pyroxene which has the Mg–Fe chemical zoning. It seems likely that the cooling rates of WALKER *et al.*'s experiments (1–70°C/hr) are so fast that Juvinas-like pyroxene cannot be produced because the absolute cooling rate of Juvinas pyroxene may be about 0.4°C/10^2 year, judging from the width of exsolution lamellae.

The hypothesis that the howardites are the surface materials of an achondrite parent body has been already proposed (REID, 1974; BUNCH, 1975; TAKEDA *et al.*, 1976b; DRAKE and CONSOLMAGNO, 1977; DYMEK *et al.*, 1976). The howardites are polymict breccias which consist of both diogenitic and eucritic fragments. Our proposed 'eucritic polymict breccia' consists of various eucritic fragments. Namely, the eucritic polymict breccia is a howardite without a diogenitic portion. In the primitive crust of an achondrite parent body, we have proposed that the diogenite layer may have been located in a deeper place than the eucrite layer (TAKEDA *et al.*, 1976b; MIYAMOTO *et al.*, 1978b). Therefore, the eucrite layer has more opportunities of the mixing processes by impact than the diogenite layer has. The fact that the eucritic polymict breccias show the strong brecciated texture and the pyroxenes contained in them have experienced the rapid cooling history suggests that the eucritic polymict breccias have been located in the surface layer of an achondrite parent body. The eucritic polymict breccia is a better candidate for the surface materials of an achondrite parent body than the howardite.

The minor planet 4 Vesta shows a unique reflection spectrum among the larger asteroids, and appears to be the only good candidate in the solar system for the achondrite parent body. Recently, LEBERTRE and ZELLNER (1978) concluded that the known optical properties of Vesta can be explained by crushed basaltic achondrites with a substantial component of very fine dust. It is interesting that our proposed eucritic polymict breccia satisfies the above conditions.

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