YAMATO ACHONDRITE POLYMICT BRECCIAS

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Abstract: Electron microprobe studies have been made of pyroxenes from Yamato-7307 and Yamato-74159. Both meteorites show the brecciated texture. Yamato-7307 was identified as howardite by us previously. It contains pyroxenes similar to those of diogenites and eucrites. However, Yamato-74159 contains various pyroxenes, calcic plagioclase, and other minerals and lithic clasts of only eucritic affinity. Within the thin section we have examined, there was found no diogenitic pyroxene. Therefore, Yamato-74159 may best be described as a eucrite polymict breccia. These two meteorites can be explained by the surface brecciation process of a proposed layered crust model on an achondrite parent body.

1. Introduction

Among achondrites, howardites, polymict breccias of diogenites and eucrites (DUKE and SILVER, 1967) have been considered to be lithified surface regolith breccias formed on a small planet-like body, a parent body of the genetically related achondrites (*e.g.* BUNCH, 1975; TAKEDA *et al.*, 1976a). Since mineral and lithic clasts of these breccias may represent various parts of the differentiated crusts of the body, and have not relatively been altered by impact processes, these achondrites will be unique source of information about the processes of crust formation which had taken place on the primitive planet.

However, we had to face the serious difficulty that the achondrites are so rare. Thus, the discovery of some achondrite polymict breccias in the Yamato Mountains range in Antarctica is important and epoch-making event (NAGATA, 1975; YOSHIDA *et al.*, 1971; KUSUNOKI, 1975; SHIRAISHI *et al.*, 1976), and give us good opportunity to study a process of crust formation and brecciation. This paper deals with two achondrite polymict breccias Yamato-7307 and Yamato-74159. Pyroxenes and other minerals in these meteorites have been studied by the combined techniques of electron microprobe analysis and the single crystal X-ray diffraction. Based on our proposed crust-model of an achondrite parent body, we will unravel the genesis of these achondrite polymict breccias.

2. Samples and Experimental Techniques

Yamato-7307, previously called Yamato (1) was found near the Yamato Mountains in East Antarctica in December 1973 by the oversnow traverse party of the 14th Japanese Antarctic Research Expedition (JARE-14) (SHIRAISHI *et al.*, 1976). This meteorite weighs 480 g. The detailed petrologic description has been given by YAGI *et al.* (1977). One broken piece we examined shows the brecciated texture. Yellowish and dark greenish yellow orthopyroxene fragments and eucritic clasts are seen in fine grained grey matrix. The optical observation of the thick section cut from this piece shows that it consists of diogenitic pyroxene fragments and eucritic clasts with pigeonite and plagioclase.

Yamato-74159 is a small stone (98.2 g) collected in 1974 (YANAI, 1976; YANAI *et al.*, 1976). A chip (0.1 g) we received had a lustorous black fusion crust on one side of the chip. It is greyish with patchs of white plagioclase.

Polished grain mounts were prepared for a preliminary microprobe examination of this meteorite. Twenty-one slices of 0.25 mm thick were cut from a small rock fragment (1.8 g) of Yamato-7307 mounted in epoxy resin. Three sections (slice No. 4, 9, 14) including one with eucritic clast were selected for the present study. One of these sections (No. 14) were cemented to a slide-glass by Lakeside 70 for easy removal of pyroxene crystals in the subsequent single crystal X-ray diffraction studies and polished thick section (about 0.15 mm thick) of the slices were made in order to carry out the microprobe analyses. The other sections were polished into the regular thin-sections.

The microprobe analyses were made of pyroxenes, representative plagioclases and opaque minerals in the polished sections to identify coexisting orthopyroxenes, augite and inverted pigeonite. Some interesting pyroxene crystals were separated from the grain mount for the single crystal X-ray diffraction studies. Similar techniques were applied to the Yamato-74159 meteorite.

The method of single crystal X-ray diffraction studies is the same as that described by TAKEDA *et al.* (1975; 1976a). The quantitative chemical analyses were made with a Japan Electron Optics Laboratory Co. JXA-5 electron probe X-ray microanalyzer with a 40° take off angle. The instrumental method was the same as that described by NAKAMURA and KUSHIRO (1970).

3. Results

Yamato-7307 is a polymict breccia consisting of large dark green and light yellow bronzite clasts, eucritic clasts and small plagioclase and olivine clasts. The photograph of Yamato-7307 thick section (Fig. 1) shows the locations of the diogenitic mineral clasts and eucritic clasts (the left portion of Fig. 1) in a

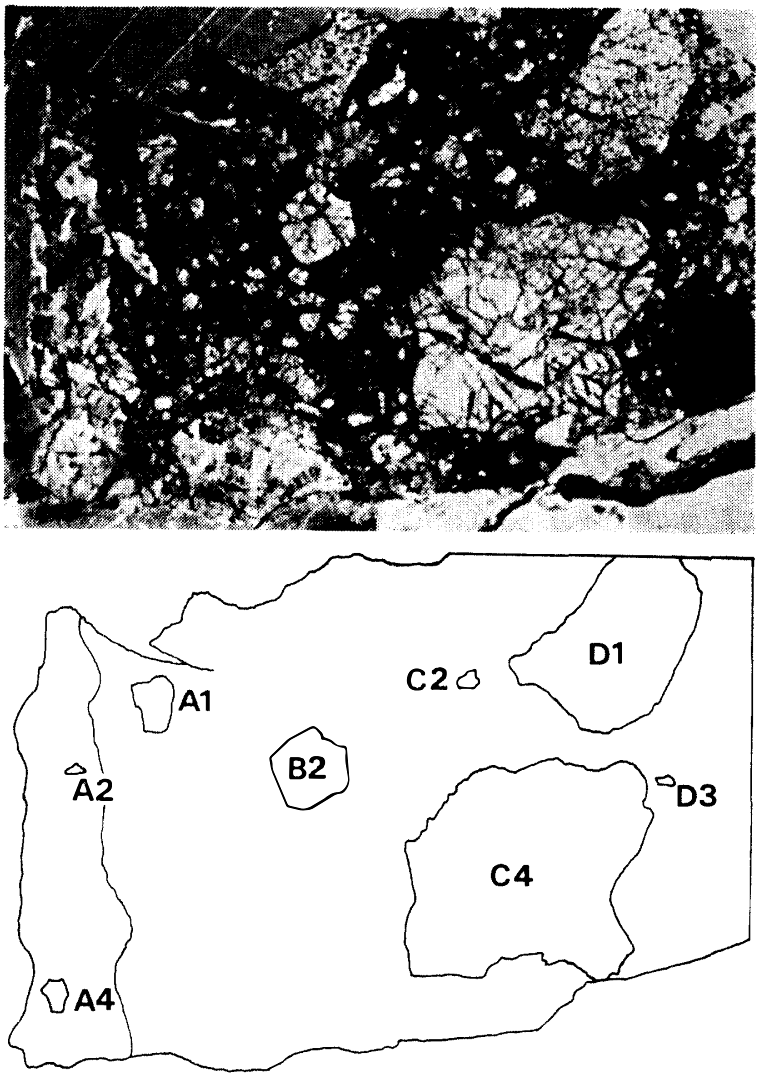

Fig. 1. Photograph and map of thick-section No. 14 of Yamato-7307 howardite. Width is 5 mm.

diogenitic matrix. The largest bronzite clasts are about 3 mm in diameter. Table 1 shows the results of electron microprobe analyses of pyroxenes in Yamato-7307. The results of chemical analyses of pyroxenes in Yamato-7307 (slice No. 9 and 14) are illustrated in Fig. 2.

One large bronzite crystal in slice No. 4 of Yamato-7307 has low-Ca composition $Ca_{0.9}Mg_{77.9}Fe_{21.2}$ (S in Table 1) similar to that of Steinbach (REID *et al.*, 1974). A crystal (D1 in slice No. 14; Table 1) contains small Mg-rich augite inclusions. A pyroxene (B2 in slice No. 14; Table 1) with chemical composition similar to that from Binda was found (Fig. 7; TAKEDA *et al.*, 1976a), and a pyroxene (A1 in slice No. 14; Table 1) has chemical composition similar to that from Moama (LOVERING, 1975). Fe-rich pigeonite crystals $Ca_{10}Mg_{37}Fe_{53}$ with regular exsolution lamellae of augite $Ca_{42}Mg_{32}Fe_{26}$ on (001) of the host clino-

Table 1. Selected electron microprobe analyses of pyroxenes (wt. %) from the Yamato-7307 howardite.

Sample	D3	C2	S	D1		Y1	C4	B2		
	Opx	Opx	Opx	Opx	Aug	Opx*	Opx*	Host	Pig*	Aug
SiO_2	55.18	54.72	55.69	54.87	53.44	53.25	53.29	53.09	53.70	52.18
Al_2O_3	0.76	0.55	0.48	0.87	0.52	1.16	1.03	0.65	0.72	0.86
TiO_2	0.06	0.04	0.03	0.09	0.08	0.07	0.12	0.30	0.37	0.55
Cr_2O_3	0.58	0.36	0.66	0.36	0.28	0.77	0.47	0.37	0.65	0.47
FeO	11.37	12.66	13.96	15.48	5.54	14.79	16.96	19.44	17.91	8.10
MnO	0.44	0.58	0.43	0.63	0.32	0.55	0.75	0.77	0.73	0.46
MgO	30.47	30.27	28.79	27.37	16.22	26.65	24.74	22.77	21.62	15.06
CaO	0.94	0.55	0.49	1.09	22.88	1.75	1.80	1.61	3.96	20.89
Na_2O	0.03	0.03	0.0	0.02	0.09	0.02	0.04	0.03	0.05	0.12
Total	99.83	99.76	100.53	100.78	99.37	99.01	99.20	99.03	99.71	98.69
Ca**	1.8	1.0	0.9	2.1	46.0	3.4	3.6	3.3	8.2	43.4
Mg	81.2	80.1	77.9	74.3	45.3	73.6	69.6	65.4	62.6	43.5
Fe	17.0	18.8	21.2	23.6	8.7	22.9	26.8	31.3	29.1	13.1

Sample	A1			C5		A4			A2
	Host	Pig*	Aug	Opx	Aug	Chy	Pig*	Aug	Aug*
SiO_2	52.95	52.20	53.30	52.22	51.51	48.26	49.82	49.75	50.27
Al_2O_3	0.54	1.40	0.52	0.30	0.43	0.32	0.42	0.79	0.95
TiO_2	0.12	0.12	0.15	0.21	0.32	0.30	0.33	0.57	0.63
Cr_2O_3	0.23	0.21	0.20	0.19	0.28	0.12	0.18	0.33	0.38
FeO	21.11	18.81	8.52	22.75	11.61	34.66	31.14	15.66	17.90
MnO	0.80	0.75	0.50	1.03	0.58	1.34	0.79	0.57	0.60
MgO	22.49	20.12	14.79	21.37	15.05	12.69	12.44	10.77	10.61
CaO	1.56	4.12	21.34	1.85	19.28	0.97	4.60	19.99	18.14
Na_2O	0.03	0.05	0.07	0.05	0.17	0.02	0.06	0.12	0.11
Total	99.83	97.78	99.39	99.97	99.24	98.68	99.78	98.55	99.59
Ca**	3.2	8.8	43.9	3.8	39.1	2.1	10.0	42.4	38.7
Ma	63.4	59.8	42.4	60.3	42.5	38.6	37.4	31.7	31.5
Fe	33.4	31.4	13.7	36.0	18.4	59.2	52.6	25.9	29.8

* Bulk composition including the exsolved phase. Chy: clinohypersthene.
** Mole per cent.

hypersthene $Ca_2Mg_{39}Fe_{59}$, similar to that from Juvinas (TAKEDA *et al.*, 1974a, b) were found in a eucritic clast in which a small augite was also found (A4 and A2 in Table 1). This type of pyroxene found in a polished grain mount has crystallo-

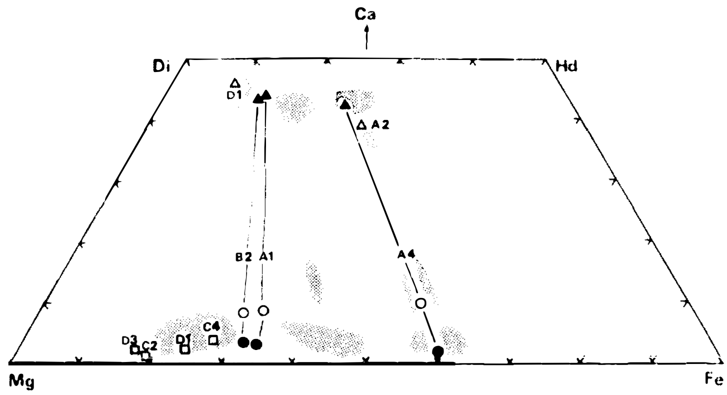

Fig. 2. Composition of pyroxenes in Yamato-7307 (filled circle: host, open circle: bulk, and triangle: lamellae). The tie line indicates coexisting host-lamellae pair. Shaded areas are the range of pyroxene compositions in Yamato-7307.

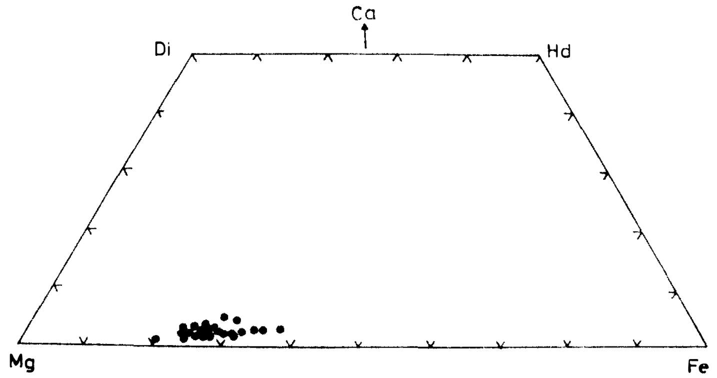

Fig. 3. Compositions of pyroxenes in Yamato-7307 matrix.

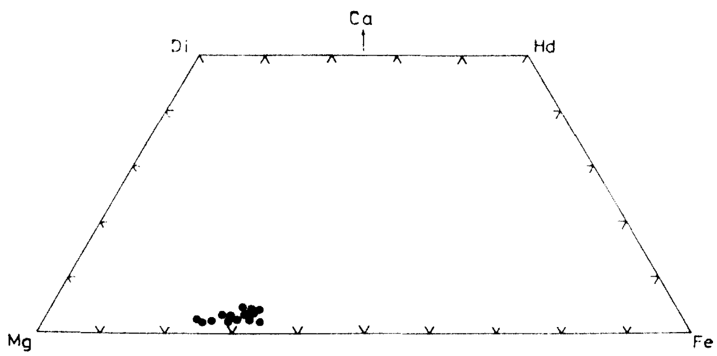

Fig. 4. Compositions of pyroxenes in a diogenitic portion of the Mt. Padbury mesosiderite.

graphic data the same as those of Juvinas (TAKEDA *et al.*, 1976). The range of chemical composition of the Yamato-7307 pyroxenes covers over that of diogenites and eucrites.

Table 2. Representative electron microprobe analyses of olivine and plagioclase (wt. %) from the Yamato-7307 howardite.

Sample	Olivine	Plagioclase		Plagioclase
SiO_2	36.70		45.49	44.60
Al_2O_4	0.02		34.60	34.26
TiO_2	0.0		—	—
Cr_2O_3	0.0		—	—
FeO	26.55		0.26	0.12
MnO	0.50		—	—
MgO	36.17		—	—
CaO	0.03		17.70	19.01
Na_2O	0.0		1.43	0.90
NiO	0.09		—	—
Total	100.06		99.48	98.89
Mg*	70.8	Or*	0.7	0.3
Fe	29.2	Ab	12.6	7.8
		An	86.7	91.9

* Mole per cent.

Table 3. Representative electron microprobe analyses of metal phase (wt. %) from Yamato-7307 howardite. Location numbers (#) are shown in Fig. 5.

	Traverse #1		Traverse #2		Traverse #3		Average			Troilite
	Hi. Ni	Lo. Ni	Hi. Ni	Lo. Ni	Hi. Ni	Lo. Ni	Grain #5	Grain #6	Grain #10	Average
Fe	91.29	93.82	79.63	93.34	85.52	94.50	45.13	45.65	92.49	63.85
Ni	7.28	4.48	18.65	4.73	12.52	3.22	53.86	54.21	5.81	0.0
Co	1.28	1.40	1.15	1.35	1.10	1.29	0.14	0.13	1.21	—
S	0.0	0.0	0.0	0.0	0.0	0.0	0.08	0.73	0.03	35.98
Total	99.85	99.70	99.43	99.42	99.14	99.01	99.21	100.72	99.54	99.83

Statistical point analyses by the microprobe techniques of the matrix pyroxenes in Yamato-7307 show that their chemical composition within the grain is uniform, but they cover all range of known diogenitic pyroxenes in the matrix (Fig. 3). The proportion of diogenite-like pyroxenes is more abundant than eucritic pyroxenes in Yamato-7307.

A few small fragments of olivine (Fa_{25}–Fa_{30}) were also found in the matrix. Table 2 shows the results of electron microprobe analyses of this olivine and plagioclase. The results of chemical analyses of a metal grain in Yamato-7307 (slice No. 4) are shown in Table 3. Fig. 5 shows electron microprobe traverses across the metal grain monitoring Ni and Co radiation.

The *h0l* precession photographs of diogenitic bronzites with CaO contents

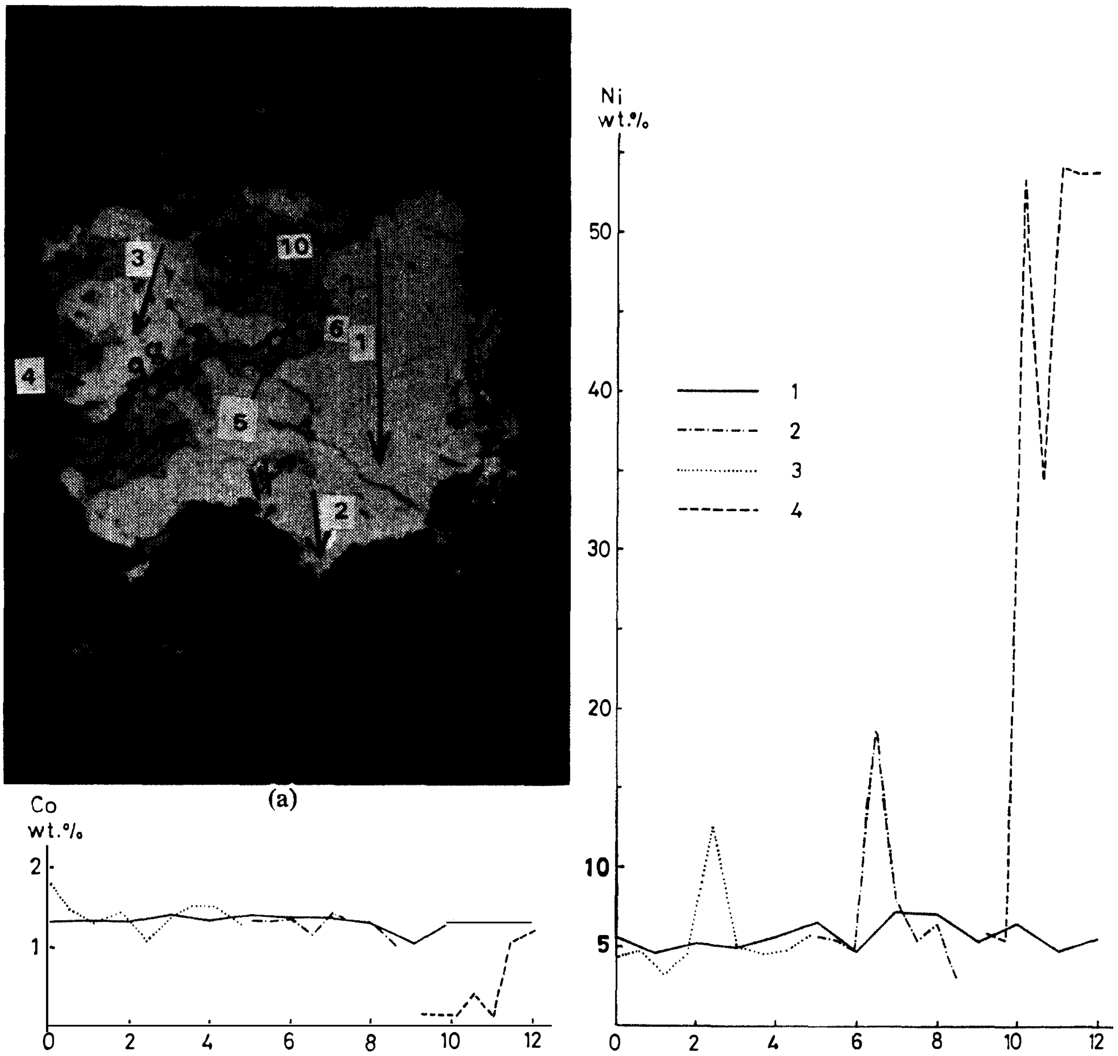

Fig. 5. Photograph and analytical traverses of a metal grain in the Yamato-7307 howardite. The size of the grain is 0.46×0.41 mm. The horizontal scale 12 corresponds to 0.24 mm.

higher than 1.3 wt.% (*e.g.* C4 in slice No. 14; Table 1) show reflections of exsolved augite with (100) in common with the host orthopyroxene, in line with our observation on pyroxenes in diogenites (MIYAMOTO *et al.*, 1975).

The optical observation of a Yamato-74159 thick section shows that it contains a Pasamonte-like eucritic clast (DUKE and SILVER, 1967) with ophitic texture in which lath-shaped plagioclase crystals are embedded in pyroxene crystals (Fig. 6). Fig. 7 shows the results of electron microprobe analyses of pyroxenes in the Yamato-74159 thick section. Chemical compositions of pyroxenes from Pasamonte-like clasts in Yamato-74159 (dotted line in Fig. 7) show that these pyroxenes exhibit unusual chemical zoning similar to that of pyroxenes in Pasamonte (TAKEDA *et al.*, 1976b) (Fig. 8).

Various other eucritic pyroxenes exist in the Yamato-74159, together with

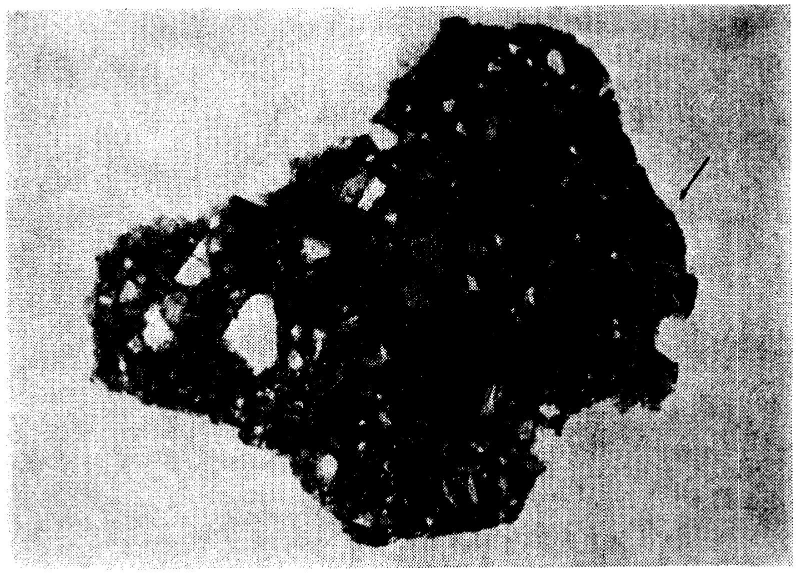

Fig. 6. Photograph of thick-section of Yamato-74159. Width is 6 mm. Arrow indicates the position of the Pasamonte-like clast.

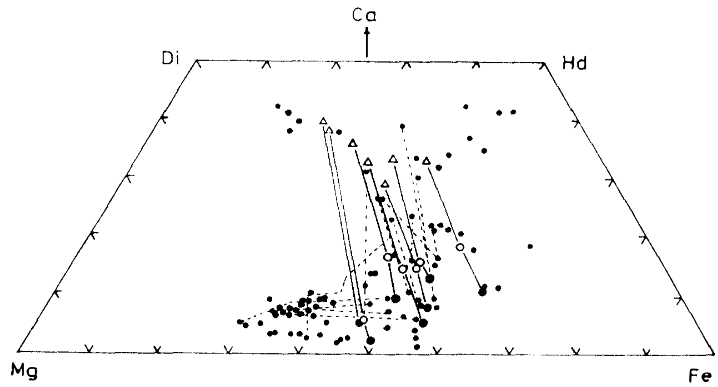

Fig. 7. Compositions of pyroxenes in Yamato-74159. Dotted lines indicate the range of continuous zoning within single crystal. The lines indicate coexisting host-lamellae pair, open circle: bulk composition.

this Pasamonte-like fragment. In addition to the lath-shaped plagioclases in the Pasamonte-like clast, this meteorite contains some Ca-rich plagioclase grains. The chemical analyses of typical Yamato-74159 pyroxenes are shown in Table 4. Chemical trends of the Yamato-74159 pyroxenes are complex (Fig. 7), but on the basis of the chemical composition and the exsolution texture, the pyroxenes in the Yamato-74159 can be grouped into three types, each of which has been known as a single meteorite: (1) Pigeonite clasts with coarse lamellae such as Moore County (Fig. 9 of MASON, 1962) (the width of exsolution lamella is about 15 micron); (2) Common eucritic pyroxenes with fine lamellae such as Juvinas (TAKEDA *et al.*, 1974b); (3) Pasamonte-like pyroxenes with chemical

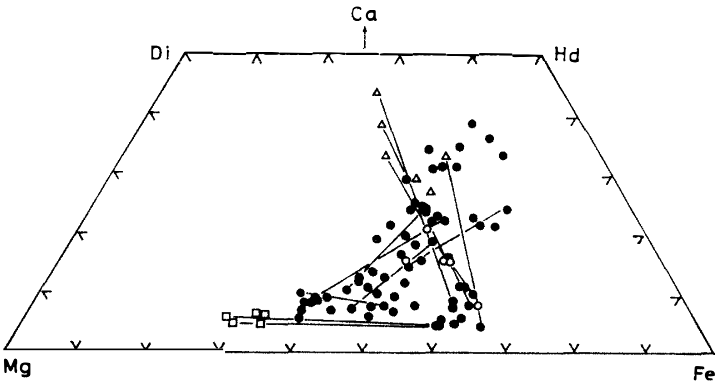

Fig. 8. Compositions of pyroxenes in Pasamonte. Lines indicate the ranges of continuous zoning within single crystal. Open circles: Bulk composition of exsolved pigeonite.

Table 4. Representative electron microprobe analyses of pyroxenes (wt. %) from Yamato-74159.

Sample	6			4			1		
	Host†	Pig*	Aug	Host	Pig*	Aug	Host	Pig*	Aug
SiO_2	51.10	51.32	51.10	49.72	49.75	49.54	48.41	47.94	48.74
Al_2O_3	0.51	0.64	1.71	0.52	0.84	1.31	0.58	0.96	1.51
TiO_2	0.54	0.61	1.16	0.57	0.70	1.08	0.58	0.63	1.08
Cr_2O_3	0.26	0.38	0.61	0.24	0.33	0.41	0.18	0.26	0.45
FeO	24.63	23.29	11.07	31.69	28.38	22.98	36.98	31.83	23.58
MnO	0.80	0.80	0.48	0.99	0.83	0.78	1.16	0.98	0.66
MgO	18.93	18.27	14.10	12.90	12.52	11.63	8.39	8.05	7.64
CaO	3.17	4.49	19.59	3.13	6.83	11.99	3.89	8.40	16.05
Na_2O	—	0.07	0.18	0.06	0.03	0.10	0.05	0.07	0.14
Total	99.94	99.87	100.00	99.82	100.21	99.82	100.22	99.12	99.85
Ca**	6.5	9.3	40.9	6.8	14.7	26.0	8.7	18.9	35.6
Mg	54.0	52.9	41.0	39.2	37.5	35.1	26.3	25.2	23.6
Fe	39.5	37.8	18.1	54.0	47.8	38.9	65.0	55.9	40.8

* Bulk composition including the exsolved phase.
** Mole per cent.
† Analysis by M. SATO.

zoning.

The pyroxene grain 6 in Yamato-74159 have coarse lamella (about 15 micron), whose bulk composition ($Ca_{9.3}Mg_{52.9}Fe_{37.8}$) is similar to that of Moore County ($Ca_{10.1}Mg_{45.6}Fe_{44.3}$) (ISHII and TAKEDA, 1974). The width of augite lamellae of Moore County is about 50 micron and thicker than that of the pyroxene grain 6. Pyroxene grain 1 ($Ca_{18.9}Mg_{25.2}Fe_{55.9}$) is similar to that in common eucrites such as Juvinas ($Ca_{8.0}Mg_{36.0}Fe_{56.0}$) and with fine lamella (about 5 micron).

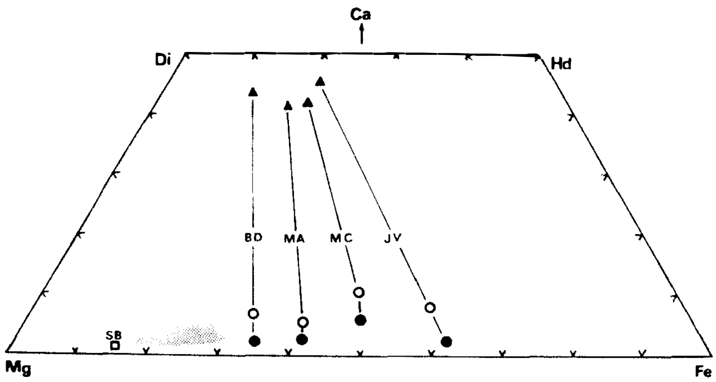

Fig. 9. Compositions of pyroxenes in representative achondrites. SB: Steinbach, BD: Binda, MA: Moama, MC: Moore County, JV: Juvinas. Shaded area indicates the range of diogenite pyroxenes.

4. Discussion

Yamato-7307 is a polymict breccia and was previously identified as a howardite (MIYAMOTO *et al.*, 1975; TAKEDA *et al.*, 1976a; MIYAMOTO *et al.*, 1976). Since the round eucritic clasts are not rare in this meteorite it may be described as polymict diogenite breccia with eucritic clast (LOMENA *et al.*, 1976).

The chemical composition of small olivine fragments in Yamato-7307 matrix is Fa_{25}–Fa_{32} (Table 2) and is not the same as that of pallasite (Fa_{10}–Fa_{20}; POWELL, 1971), but is similar to that of mesosiderite. The chemical composition of metal phase in achondrites is generally high in Co content and is nearly pure iron phase (POWELL, 1969). However a metal grain in Yamato-7307 belongs to kamacite-taenite phase (Fig. 5; Table 3). The chemical trend of orthopyroxenes in the Yamato-7307 matrix (Fig. 3) is similar to that in diogenitic portion of a mesosiderite in Fig. 4 (Mt. Padbury; MCCALL, 1966). Therefore, the chemical compositions of minerals and brecciated texture of Yamato-7307 resemble those of metal poor, lithic portion of some mesosiderites.

Yamato-74159 is a unique meteorite in its brecciated texture and pyroxene compositions. The texture and mineral compositions of Yamato-74159 resemble those of Ca-rich howardite (REID, 1974) which is a polymict breccia. However. within the thin section we have examined, there was found no diogenitic pyroxenes. The most Mg-rich pyroxenes found rarely as fine grains in the matrix are similar to that found in the Pasamonte eucrites. It appears to belong to the eucrite group on the basis of the pyroxene compositions and bulk chemistry alone, but the texture of this meteorite is different from that of any known eucrites.

Chemical trend of the Yamato-74159 pyroxenes are complex (Fig. 7) and this meteorite contains some Ca-rich plagioclases. The mixture of the Pasamonte-like pyroxenes with chemical zoning and various eucritic pyroxenes with uniform chemical composition give rise the complexity of the pyroxene trends. Therefore, Yamato-74159 may best be described as a polymict breccia with various, eucritic clasts (eucrite polymict breccia). However, we cannot exclude the possibility that the diogenitic portion will be found in other portion of Yamato-74159, because the samples we examined in this study is a very small chip near surface of the meteorite. If Yamato-74159 contains a diogenitic clast in other part it should better be called as Ca-rich howardite. Because Moore County is considered to be a cumulate, which had sunk to bottom of eucritic crust of the parent body, and experienced more slow cooling than the Moore County-like grain 6 in Yamato-74159, Yamato-74159 may represent a excavated material by an impact process shallower than that of Moore County. The Juvinas-like pyroxenes in Yamato-74159 cooled more rapidly than the grain 6 and seems to be located at the upper portion of eucritic crust than the grain 6.

Besides the above pyroxenes with uniform chemical compositions, there are pyroxene clasts with chemical zoning such as those found in the Pasamonte eucrite. A Pasamonte-like eucritic clast with fine ophitic texture also exists. As was reported (TAKEDA *et al.*, 1976b) a proposed possible origin for the Pasamonte is the surface lava extruded on the surface of achondrite parent body or the solidified materials of the impact melt of a surface of the parent body or outer most thin layer of the crust of the parent body. The clast with ophitic texture in Yamato-74159 seems to have the same origin as the Pasamonte eucrite. If we had not recognized the Pasamonte type pyroxenes, the Yamato-74159 meteorite would have been interpreted as a mixture of some unrelated rock types. Conversely, Yamato-74159 shows the evidence of the close genetic relationship between Pasamonte eucrite and other eucrites.

We have proposed a layered-crust model of the achondrite parent body on the basis of crystallographic characteristics and chemical trend of pyroxenes in diogenites, eucrites and howardites (TAKEDA *et al.*, 1976a) and depth beneath the surface estimated from the width of exsolution lamellae of augite in pigeonite (MIYAMOTO, 1976). A proposed crust model has layered structure with pyroxenes from bottom to top as: Steinbach-like Mg-rich, very Ca-poor bronzite; Shalka-like magnesian bronzite; less Mg-rich, Ca-rich bronzite; Binda-like Mg-rich, Ca-poor inverted pigeonite with blebs of augite with (100) in common; Moore County-like Ca-rich inverted pigeonite with coarse (001) augite lamella; Juvinas-like pigeonite with fine (001) augite lamella, and Pasamonte-like pyroxenes with extensive chemical zoning.

The presence of heavily cratered terrain on Mercury, Mars, Moon, Phobos, and Deimos confirmed by many planetary probes, suggests that the brecciation by impact is common phenomena on the terrestrial planets and their satellites in the early stage of the evolution of these bodies. We, therefore, can naturally accept an idea that impact phenomena had been active on the achondrite parent body.

The presence of polymict breccias such as eucrite polymict breccia (Yamato-74159) and howardites (*e.g.* Yamato-7307) can be explained by the surface brecciation process on the achondrite parent body (MIYAMOTO *et al.*, 1977) and the layered-crust model proposed by us (TAKEDA *et al.*, 1976a, b; MIYAMOTO, 1976).

A large meteorite impact may excavate the crust of achondrite parent body more deeply than a small one does. On the site where the Yamato-74159 breccia was developed, the meteorite impact may have excavated only the shallower portion of the crust, namely the eucritic upper portion. On the other hand, a large meteorite impact may have excavated the materials deep in the crust including diogenites together with various portion of the eucritic crust materials. The howardites may represent lithified materials of such products. This mechanism is consistent with the view that howardite is the polymict breccia which contains wide range of materials including typical end-member materials of diogenites and eucrites.

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