

# MINERALOGICAL EXAMINATION OF THE ALLAN HILLS ACHONDRITES AND THEIR BEARING ON THE PARENT BODIES

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**Abstract:** Mineralogical examination of the Allan Hills achondrites collected by the U.S.-Japan joint team in the 1977 and 1978 seasons, except ALHA78113 and previously reported ALHA77005 and ALHA77302, revealed that they are polymict eucrites except two ureilites ALHA77257 and ALHA78019, and diogenite ALHA77256 and a primitive achondrite, ALHA77081. Among four polymict eucrites, ALHA78006 contains minor diogenitic components. The existence of such a polymict breccia can be explained in terms of excavation and mixing by impacts down to a very upper portion of the diogenite layer of a layered crust model of our howardite parent body. The MnO/FeO ratios of ALHA77081 lie on the extension of the equilibrated chondritic trend and the mineralogy is compatible with a primitive achondrite such as Winona. A coexisting pigeonite-orthopyroxene pair has been found in two Mg-rich Antarctic ureilites. On the basis of mineralogy of five Antarctic ureilites, an origin connected with a planetesimal produced by a fragmentation of the solar disk has been discussed.

## 1. Introduction

In our series of papers on the Yamato achondrites published previously, we have described all important Yamato achondrites among 30 diogenites, 8 eucrites, 1 howardite and 3 ureilites newly found, and discussed how the previous models of the achondrite parent body or bodies had to be modified because of the new findings of many unique Antarctic achondrites (TAKEDA *et al.*, 1978, 1979a, b). For example, one of the most Fe-rich diogenites, Yamato-75032, containing the low-Ca inverted pigeonite gave a strong support on the genetic link between diogenites and eucrites. The eucritic polymict breccias, which are polymict breccias of eucritic compositions or howardites without diogenitic components, and are found abundantly in the Yamato meteorite collection, have contributed to the reconstruction of the crust model on the

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howardite parent body or bodies (TAKEDA, 1979). The Yamato diogenites with a granoblastic texture gave us some clues on the recrystallization processes in the diogenitic mantle. Extreme chemical compositions outside the known range found in the Yamato ureilites gave us an opportunity to test many controversial hypotheses proposed for the origin of ureilites.

Table 1. Allan Hills achondrites.\*

Meteorites	Mass	Remark	Meteorites	Mass	Remark
ALHA77005	482.5 g	Unique	ALHA77302	235.5 g	Eucrites
ALHA77219	637.1	Mesosiderite	ALHA78006	8.0	Howardites
ALHA78113	298.6	Aubrite	ALHA78040	211.7	Eucrite
ALHA77256	676.2	Diogenite	ALHA78132	656.0	"
ALHA77257	1995.7	Ureilites	ALHA78158	15.1	"
ALHA78019	30.3	"	ALHA78165	20.9	"
ALHA76005**	1435	Eucrites			

\* See YANAI *et al.* (1978), YANAI (1979), MASON (1978, 1979).

\*\* Allan Hills-765.

It is interesting to see how some of the characteristics found in the Yamato meteorites are exhibited by the Allan Hills achondrites. Among the Allan Hills achondrites, eucritic polymict breccias are also common, and Allan Hills-765 and ALHA-77302 have been studied previously (MIYAMOTO *et al.*, 1978, 1979). Many more such eucrites have been found by the 1978-79 U.S.-Japan joint team for search for the Antarctic meteorites (SHIRAISHI, 1979) (Table 1). ALHA78006 has been described in this paper, because of the occurrence of small diogenitic components and the Moore County type inverted pigeonite. The occurrence of such polymict breccia poses some problems in classification of achondrites. The term, eucritic polymict breccia has been used in our previous paper on the Antarctic achondrites. Since "polymict eucrite" has been defined as a better terminology in our separate paper (TAKEDA *et al.*, 1980), we use this terminology instead of eucritic polymict breccias in the subsequent paper.

A preliminary mineralogical study on the ALHA77256 diogenite has been given previously (TAKEDA, 1979). A more detailed study on its exsolution texture by the TEM technique is given in this paper. Two Allan Hills ureilites are compared with the unique Yamato ureilites. A possible coexistence of pigeonite and orthopyroxene in the ureilites is mentioned. Of the two unique meteorites, ALHA77005 has been described in detail by ISHII *et al.* (1979) and MCSWEEN *et al.* (1979), and will not be dealt with in this paper. The other one, ALHA77081, which is similar to Acapulco, an intermediate member between the E and H types (MASON, 1978), is described in this paper, especially, on the MnO/FeO fractionation trends and the equilibration

temperature. The MnO enrichment mechanism of this meteorite and chondrites is discussed and is applied to constrain the origin of ureilites.

## 2. Samples and Experimental Techniques

Preliminary descriptions of the samples are given in the Antarctic Meteorite Newsletter by Brian MASON (1979). The numbers and the amounts (in parentheses) of samples supplied for the present study are: ALHA77256, 83 (3.188 g), 77256, 84 (0.175), 77257, 72 (2.769), 77081, 80 (0.355). Polished thin sections ALHA77256,6, 77257,8, 77081,4 supplied by NASA-Smithsonian Institution, and ALHA78006,5 and 78019,5 prepared for K. SHIRAISHI of the National Institute of Polar Research at the NASA-JSC were employed for the microprobe and microscopic examinations. An epoxy mount (potted butt) prepared from a part of the above chips was sliced to produce one or two polished thin sections. For relatively large samples, one thick section cemented by Stick-wax was produced and was finished (polished) to about 0.1 mm thick so that single crystals of particular compositions could be separated after microprobe analyses. The bulk chemistries of ALHA77256 and ALHA77132 were obtained by a standard wet-chemical method by Mr. H. HARAMURA of the University of Tokyo through the courtesy of Professor I. KUSHIRO of the Geological Institute.

For a new identification of small achondrites for distribution, small chips of ALHA78006,50(0.381 g), 78019,50(0.103), 78158,91(0.075), 78165,92(0.066), and 78132,61(2.190) were supplied from the curator. A small epoxy mount was prepared for each of the above samples and was sliced to produce one polished thin section for each mount.

The quantitative chemical analyses of minerals were made with a JEOL JXA-5 electron probe X-ray microanalyzer with a 40° take-off angle. The method is the same as that of KUSHIRO and NAKAMURA (1970). A few single crystals of pyroxenes and olivines in ALHA77256, 77081, 78006, and 78019 were separated from a chipped surface of the specimens. The pyroxene crystals were mounted approximately along the *c*-axis, and were aligned with the spindle axis parallel to the *c*\* direction. Precession photographs of *h0l* nets were taken using Zr-filtered Mo *K* $\alpha$  radiation. Subsequently the crystals were mounted in araldite with a particular crystallographic axis perpendicular to a slide glass, and were polished to prepare thin oriented single-crystals for the microprobe and optical study. After the X-ray and optical examinations, the orthopyroxenes and olivines of the ALHA77256 diogenite were ion-thinned for a transmission electron microscopic (TEM) observation at 100 kV.

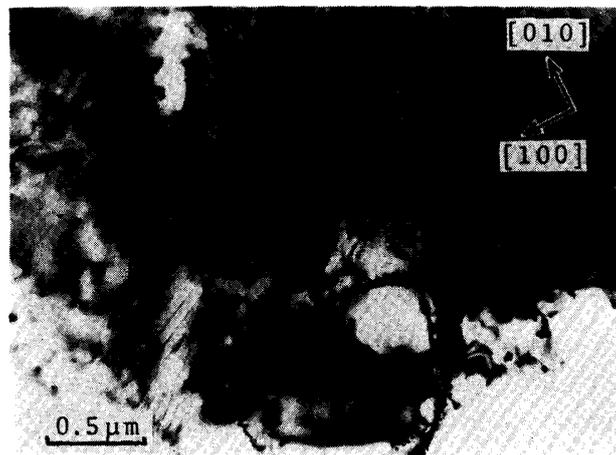
## 3. Results

### 3.1. Diogenite, ALHA77256

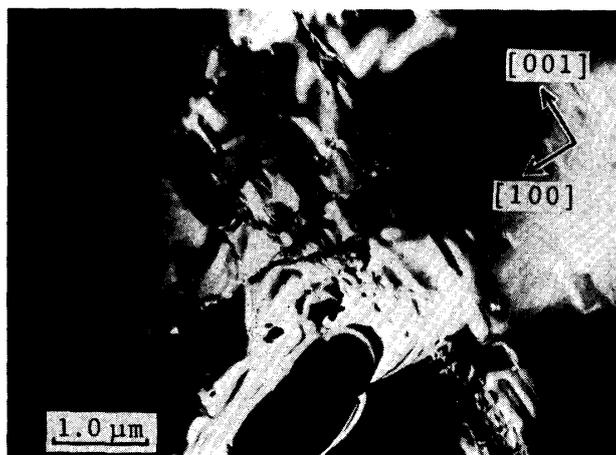
This diogenite is a monomict breccia with angular clasts set in a more com-

minuted matrix of their fragments, which forms a vein-like texture filling the interstices of the clasts. Some clasts consist of a few orthopyroxene crystals about 1  $\mu\text{m}$  in size joined by a  $120^\circ$  triple-points juncture. The texture is common among the diogenites but is different from the Yamato diogenites, which show a recrystallized granoblastic texture. Small grains of augite are present both at some junctions and within crystals. Some grains at the junction are larger than those within the crystals. Chromite and troilite are minor phases.

Olivines are not rare. The bulk chemistry of this diogenite (analysis by H. HARAMURA, in TAKEDA, 1979) is richer in olivine components than other diogenites as plotted on the silica-olivine-anorthite pseudoternary (silica 39.4%, olivine 58.7%, anorthite 1.9%). Olivine crystals ( $\text{Fa}_{28}$ ) are light yellow and are up to 4.0  $\mu\text{m}$  in length. The olivine showed complex low-angle subboundaries which were composed



a. Olivine (bright field image).



b. Orthopyroxene (dark field image).

Fig. 1. Electron micrographs of dislocations in minerals in the ALHA77256 diogenite.

of (100) dislocations (Fig. 1a). In addition, high density of straight (001) dislocations was also observed in some areas (MORI and TAKEDA, 1980).

Orthopyroxenes ( $\text{Ca}_{2.2}\text{Mg}_{73.9}\text{Fe}_{23.9}$ ) show small amounts of exsolution lamellae of augite with (100) in common with the host. The width of the lamellae ranges from 470 Å to 700 Å (mean 600 Å). The lamellae are widely spaced. The TEM study showed the orthopyroxene had fairly high density of stacking faults and dislocations. Much of the dislocations were arrayed into low-angle subboundaries (Fig. 1b). The minor exsolution of augite preferentially occurred at these subboundaries. The X-ray diffraction study indicates that the reflections of the exsolved augites are not always detected.

### 3.2. *Polymict eucrites (eucritic polymict breccias)*

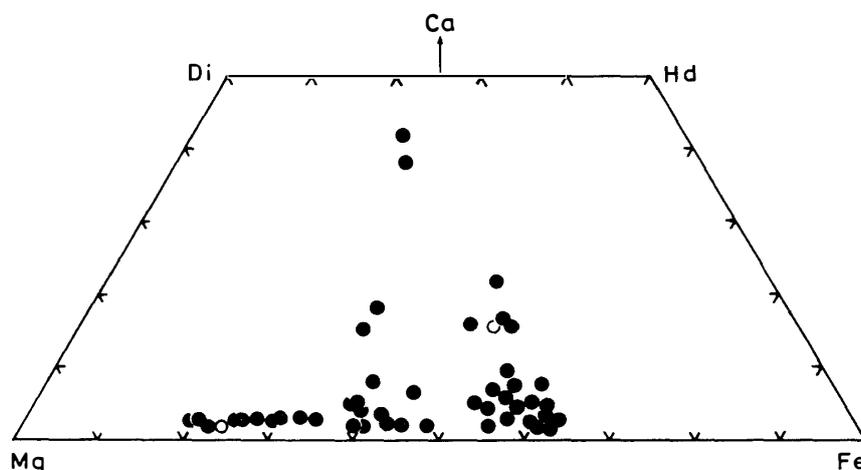
Allan Hills-765 and ALHA77302 have been identified to be similar to eucritic polymict breccias, which were first found in the Yamato meteorite collection (MIYAMOTO *et al.*, 1978, 1979). On the basis of their chemical compositions, exsolution textures and chemical zoning of pyroxene, the components of the layered crust model of a howardite parent body (TAKEDA, 1979) have been identified in these polymict breccias as: (1) Pasamonte(PM)-type pigeonite with extensive chemical zoning and (2) Juvinas(JV)-type pigeonite with uniform chemical compositions and fine, regular exsolution of augite with (001) in common with the host.

One of the characteristics of these eucrites lies in that they include pyroxenes with both chemical zoning and exsolution. Taking these additional facts into account, we classified pyroxenes of the PM-type into three subgroups. (A) Pigeonite crystals with a chemically uniform core and thin Fe-rich rim; (B) Chemically zoned pigeonite crystals with more Fe-rich core than A and very fine exsolution textures; and (C) Pyroxene grains with both A and B. These pyroxenes are intermediate members between PM-type and JV-type. A large dark clast ( $1.2 \times 1.4$  cm in size) in ALHA-77302 contains large pigeonite phenocrysts up to 5 mm in the longest dimension set in a fine variolitic matrix of plagioclases and Fe-rich pigeonites. The phenocryst pigeonite is the same as that of A.

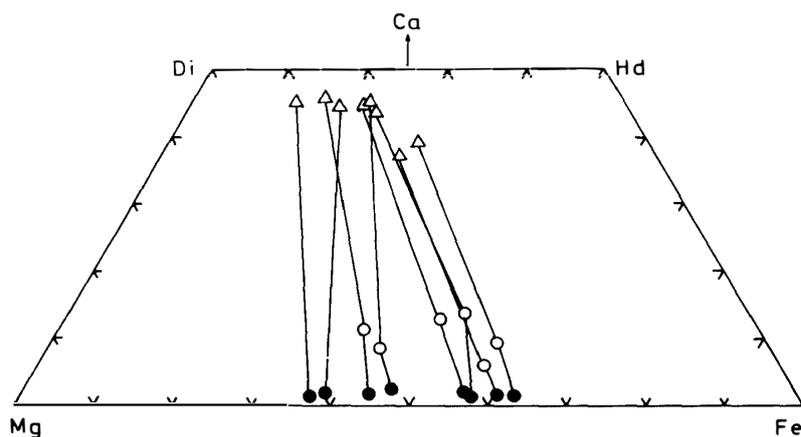
ALHA78040, 78132, 78158 and 78165 are similar to ALHA77302 in pyroxene mineralogy. Some meteorites contain JV-type pyroxenes with coarser exsolution lamellae than those of ALHA77302. Because the thin sections made for this preliminary examination were so small that the difference observed among them may be that in a portion of a larger mass. We agree with MASON's conclusion that in the absence of evidence to the contrary it appears that ALHA78158 and ALHA78132 are probably pieces of a single meteorite. A hypothesis that they could all be pieces of a single meteorite requires further study. However, ALHA78006, which is also a polymict breccia of eucrites, shows mineralogy different from the rest of the Allan Hills eucrites as described below.

### 3.3. *Polymict eucrite with minor diogenites, ALHA78006*

This achondrite is a polymict (or genomict) breccia rich in eucritic components, similar to Yamato-75015 (TAKEDA *et al.*, 1979a). It consists largely of pyroxene clasts up to 0.8 mm, and plagioclase clasts up to 0.3 mm, in a more comminuted matrix of these minerals. The proportion of the plagioclase fragments is roughly one-third of the pyroxenes. The thin section contains a large (2.5 × 1.5 mm) clast of finely recrystallized texture, eucritic clasts (0.7 × 0.6 mm) consisting of plagioclase



a. Compositions of all pyroxene fragments greater than about 0.1 mm in diameter in an entire thin section. Open circle: single crystals used for the X-ray diffraction study.



b. Compositions of exsolved pyroxenes. Open circle: bulk composition of pigeonite, filled circle: host orthopyroxene or pigeonite, triangle: augite lamellae. The tie line connects exsolved pairs.

Fig. 2. Pyroxene quadrilaterals for ALHA78006, polymict eucrites with minor diogenitic pyroxenes or howardite.

Table 2. Representative pyroxene compositions (wt%) of ALHA78006, 5.

Minerals	Diog., Ph 34 Opx bulk	MC, Ph 2		PM, Ph 36	JV, Ph 21	
		Opx host	Aug lam.	Pig core	Pig host	Aug lam.
SiO <sub>2</sub>	53.7	49.5	50.6	52.6	51.0	51.2
Al <sub>2</sub> O <sub>3</sub>	1.29	0.64	1.07	1.14	0.43	1.08
TiO <sub>2</sub>	0.07	0.27	0.64	0.17	0.03	0.67
Cr <sub>2</sub> O <sub>3</sub>	0.94	0.23	0.36	0.73	0.11	0.34
FeO	13.30	24.2	8.85	16.85	27.8	8.66
MnO	0.44	0.74	0.34	0.52	1.02	0.30
MgO	28.0	20.7	13.80	24.8	17.46	14.10
CaO	1.45	0.77	22.6	1.66	0.85	22.4
Na <sub>2</sub> O	0.03	0.00	0.25	0.01	0.02	0.11
Total	99.22	97.05	98.51	98.48	98.72	98.86
Cations (Oxygen=6)						
Si	1.945	1.937	1.931	1.949	1.987	1.940
Al	0.055	0.030	0.048	0.049	0.020	0.048
Ti	0.002	0.008	0.018	0.004	0.001	0.019
Cr	0.027	0.007	0.011	0.023	0.004	0.010
Fe	0.403	0.792	0.283	0.522	0.906	0.275
Mn	0.014	0.024	0.011	0.017	0.034	0.010
Mg	1.510	1.206	0.785	1.378	1.015	0.797
Ca	0.056	0.032	0.926	0.068	0.035	0.909
Na	0.002	0.000	0.019	0.001	0.001	0.008
Total	4.014	4.036	4.032	4.011	4.003	4.016
Ca*	2.8	1.6	46.4	3.5	1.8	45.9
Mg	76.7	59.4	39.4	70.0	51.9	40.2
Fe	20.4	39.0	14.2	26.5	46.3	13.9

\* Atomic percent.

and pigeonite with exsolution lamellae of augite on (001), and dark matrix inclusions.

Microprobe analyses show that the pyroxenes can be grouped into four types in terms of the layered crust model: Rare diagenetic orthopyroxenes (D), Moore County (MC)-type inverted pigeonites, Juvinas(JV)-type pigeonites and Pasamonte(PM)-type chemically zoned pyroxenes.

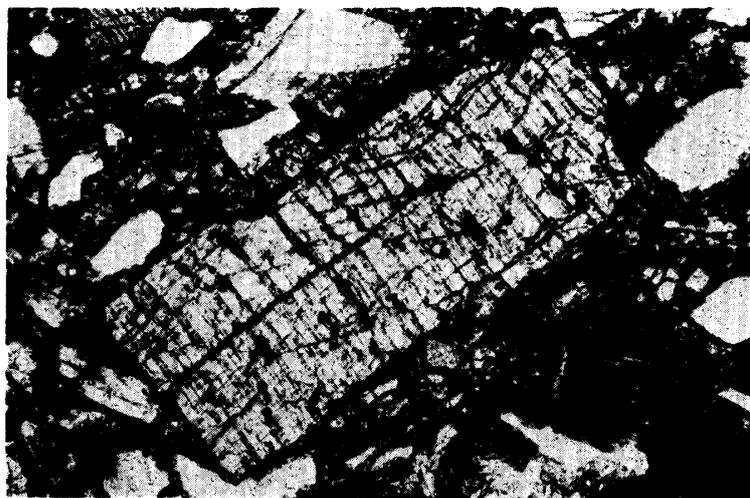
D-type: The most Mg-rich pyroxene has a diagenetic composition. The composition of an individual grain is uniform, but it differs from grain to grain. The range in the Fe/(Mg+Fe) ratios of the D-type pyroxenes with Ca contents less than 3 (mol)% is from 0.20 to 0.30 (Fig. 2a). The largest D-type pyroxene is 0.50×

Table 3. Representative chemical compositions (wt%) of olivines in ALHA78006, 5 and ALHA77081, and ureilites ALHA 77257, and 78019.

Samples	Poly. Euc.	Prim. Ach.	Ureilite		
	ALHA78006 Ph 28	ALHA77081 Ph 21	ALHA77257		ALHA78019 Ph 17
			Ph 11	Ph 24	
SiO <sub>2</sub>	36.5	39.7	39.3	39.3	37.5
Al <sub>2</sub> O <sub>3</sub>	0.01	0.01	0.03	0.03	0.02
TiO <sub>2</sub>	0.00	0.00	0.00	0.00	0.03
Cr <sub>2</sub> O <sub>3</sub>	0.01	0.01	0.70	0.74	0.72
FeO	26.5	9.75	12.96	11.30	21.1
MnO	0.67	0.49	0.43	0.49	0.42
MgO	35.7	48.3	45.1	47.1	39.1
CaO	0.03	0.02	0.34	0.34	0.41
Na <sub>2</sub> O	0.04	0.00	0.01	0.01	0.01
K <sub>2</sub> O	0.00	0.00	0.00	0.00	0.00
Total	99.46	98.28	98.87	99.31	99.31
Cations (Oxygen = 4)					
Si	0.985	0.993	0.994	0.982	0.984
Al	0.000	0.000	0.001	0.001	0.001
Ti	0.000	0.000	0.000	0.000	0.001
Cr	0.000	0.000	0.014	0.015	0.015
Fe	0.591	0.204	0.274	0.237	0.462
Mn	0.015	0.010	0.009	0.010	0.009
Mg	1.422	1.799	1.698	1.756	1.525
Ca	0.002	0.001	0.009	0.009	0.011
Na	0.002	0.000	0.000	0.000	0.001
Total	3.017	3.007	2.999	3.010	3.009
Atomic %					
Mg	70.6	89.8	86.1	88.1	76.8
Fe	29.4	10.2	13.9	11.9	23.2

0.40 mm (Ph34 in Table 2). Among the pyroxene fragments larger than 0.1 mm in diameter, about 5% are diagenetic (Fig. 2). One pale green crystal about the same size as Ph34 exposed on a chip surface gave single crystal X-ray diffraction patterns compatible with the diagenetic orthopyroxene. Diagenetic olivines are present (Ph28 in Table 3).

MC-type: Inverted pigeonites with bulk composition around Ca<sub>11</sub>Mg<sub>50</sub>Fe<sub>39</sub> (Fig. 2b) with widely spaced exsolution lamellae (10–20 μm) of augite Ca<sub>46</sub>Mg<sub>37</sub>Fe<sub>17</sub> on (001) are similar to those in the cumulate eucrite, Moore County. The largest MC-



a. Moore County-type inverted pigeonite with thick augite lamellae.



b. Juvinas-type uniform pigeonite with fine exsolution lamellae of augite with (001) in common. Upper left fragment.

Fig. 3. Photomicrographs of pyroxene clasts in ALHA78006, polymict eucrite with minor diagenetic components. Width: 0.95 mm.

type fragment is  $0.75 \times 0.30$  mm, elongated perpendicular to the plane of the augite lamellae (Fig. 3). The most Mg-rich inverted pigeonite ( $0.38 \times 0.25$  mm) is composed of two orthopyroxene crystals inverted from the host pigeonite in different orientation. The two orthopyroxenes show fine augite lamellae exsolved from orthopyroxene with (100) in common.

JV-type: Fe-rich pigeonites with compositions around  $\text{Ca}_8\text{Mg}_{35}\text{Fe}_{57}$  (Ph21 in Table 2) with fine regular exsolution lamellae of augite on (001). Pyroxenes in many common eucrite-type clasts are pigeonite with compositions similar to this type. The

intervals between the exsolved augite lamellae are wider than the common JV-type pyroxene. A brown crystal up to 1 mm in diameter exposed on the chipped surface gave a single-crystal X-ray diffraction pattern of pigeonite partly inverted to orthopyroxene.

The observation may be an indication of equilibration in eucrites (REID and BARNARD, 1979). Most of the JV-type pyroxenes found in other polymict eucrite seem to be primary, because an intermediate member between JV- and PM-types occurs in some breccias (MIYAMOTO *et al.*, 1979).

PM-type: Mg-rich pyroxene (pigeonite)  $\text{Ca}_3\text{Mg}_{70}\text{Fe}_{27}$  (Ph36 in Table 2), which may be the fragments of a uniform core of chemically zoned pigeonites similar to those found in Yamato-74450 and a porphyritic pigeonite-basalt clast in ALHA77302. The largest such fragment reaches  $0.75 \times 0.25$  mm. The fragment is elongated perpendicular to cleavage-like fracture, suggesting a fragment from rapidly cooled pigeonite. No exsolution of augite has been detected by the microprobe scan. The clast which includes the PM-type pyroxene was not found. One small clast has parallel laths of alternating plagioclase and pigeonite. This texture is common in round clasts in Yamato-75015. The presence of PM-like pyroxenes was recognized in Macibini (REID, 1974), which was one of the first polymict eucrite described, but the distinction between pyroxenes of other types was not clear at that time.

#### 3.4. Ureilites, ALHA77257 and ALHA78019

The ALHA77257 ureilite is resistant to cutting, but is relatively brittle. Crystals with somewhat curved crystal faces are often observed on the broken surface (Fig. 4). Some grains are covered with black fine-grained material and others with a

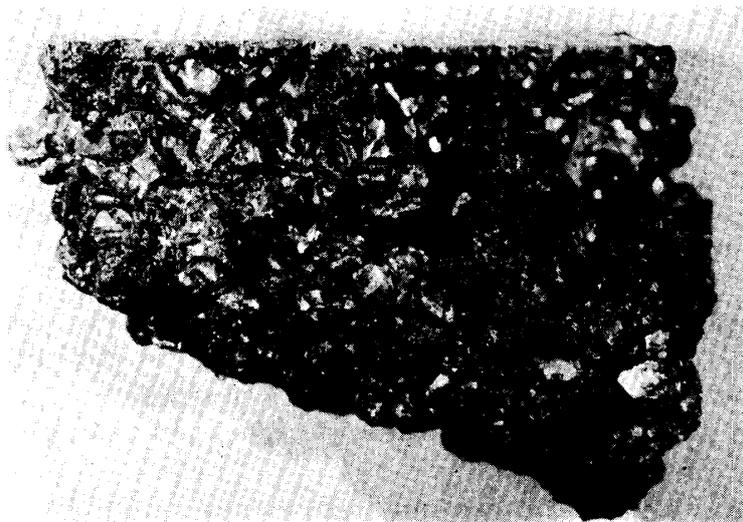


Fig. 4. Fractured surface of the ALHA77257 ureilite fragment with euhedral olivine crystals. Width of the chip is 2 cm.

dark stain. A similar fractured surface was observed on ALHA78019. Yamato-74659 does not exhibit such feature and exhibits a complex pattern of dark material and dark green fractured minerals. ALHA77257 is fairly coarse-grained, with olivine grains up to 3 mm within the thin section examined.

Our observation agrees with the description by MASON (1978) that ALHA77257 consists almost entirely of anhedral to subhedral olivine (~80%) and pyroxene (~15%). The olivine grains show abundant fractures and undulose extinction. A few small olivine crystals partly enclosed by pyroxenes have round grain boundaries. Some pyroxene grains showing coarse polysynthetic twinning, have two kinds of fractures. One kind of fracture goes through the twin boundary but the other kind is present only within one twin band and cut by the previous fractures. All grain boundaries are almost evenly filled with dark carbonaceous material, in which trace amounts of troilite and iron metal are scattered.

The chemical compositions of olivine are uniform except at the rim where the extreme Mg-enrichment is observed towards the grain boundary. This reverse chemical zoning is one of the characteristics of the ureilite olivine. Random microprobe analyses of various parts of many grains of olivine show that the compositions vary from  $Fa_{15}$  to  $Fa_4$  (Fig. 5). The core compositions (Table 3) are uniform from grain to grain, giving the mean value  $Fa_{13.8}$  with % mean deviation of 3.1 %. We

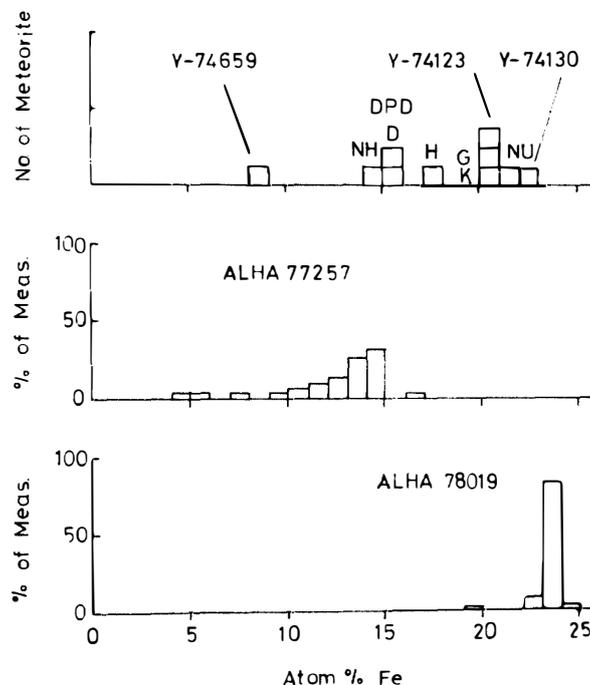


Fig. 5. Olivine compositions of ALHA77257 and ALHA78019 and other ureilites. Data of DPD: Dingo Pup Donga, D: Dyalpur, G: Goalpara, H: Haverö, K: Kenna, NH: North Haig, NU: Novo Urei are after BERKLEY et al. (1978).

Table 4. Representative pyroxene compositions (wt%) of the Antarctic ureilites.

Sam- ples	Yamato-					ALHA 77257		ALHA 78019
	74123		74130	74659		Pig P9-7	low Ca P11-7	Pig P82
	Pig P18	Pig P14	Aug P23	Pig P12-5	low Ca P16-6			
SiO <sub>2</sub>	53.2	54.4	52.3	56.6	56.6	56.0	56.3	54.2
Al <sub>2</sub> O <sub>3</sub>	0.43	0.44	2.74	0.54	0.48	0.61	0.66	0.53
TiO <sub>2</sub>	0.05	0.05	0.20	0.11	0.08	0.06	0.05	0.05
Cr <sub>2</sub> O <sub>3</sub>	1.15	1.14	1.84	0.87	0.81	1.12	1.09	1.06
FeO	12.04	11.96	7.91	5.52	5.35	8.17	7.87	12.23
MnO	0.39	0.41	0.34	0.53	0.42	0.44	0.39	0.41
MgO	27.8	27.8	18.68	32.2	33.6	30.0	31.1	26.13
CaO	3.67	3.57	14.84	3.87	2.39	3.47	2.32	4.87
Na <sub>2</sub> O	0.05	0.05	0.87	0.07	0.04	0.03	0.04	0.03
Total	98.78	99.82	99.72	100.31	99.77	99.90	99.82	99.51
Cations (Oxygen=6)								
Si	1.941	1.958	1.920	1.966	1.966	1.975	1.976	1.965
Al (IV)	0.018	0.019	0.080	0.022	0.020	0.026	0.027	0.023
Al (VI)	0.000	0.000	0.039	0.000	0.000	0.000	0.000	0.000
Ti	0.001	0.001	0.006	0.003	0.002	0.002	0.001	0.002
Cr	0.033	0.032	0.053	0.024	0.022	0.031	0.030	0.030
Fe	0.367	0.360	0.243	0.161	0.156	0.241	0.231	0.371
Mn	0.012	0.013	0.011	0.016	0.012	0.013	0.011	0.013
Mg	1.512	1.492	1.022	1.671	1.743	1.579	1.629	1.413
Ca	0.143	0.138	0.584	0.144	0.089	0.131	0.087	0.189
Na	0.004	0.003	0.062	0.004	0.003	0.002	0.003	0.002
Total	4.031	4.016	4.020	4.011	4.013	4.000	3.995	4.008
Ca*	7.1	6.9	31.6	7.3	4.5	6.7	4.4	9.6
Mg	74.7	75.0	55.3	84.6	87.7	80.9	83.7	71.6
Fe	18.2	18.1	13.1	8.1	7.8	12.4	11.9	18.8

\* Atomic percent.

tested the variation of chemical compositions of three olivine grains forming a triple-point juncture. The variation within the core portion is the same as that between the grains.

The pyroxene compositions are uniform both within the grains and from grain to grain (Table 4). The mean value is Ca<sub>6.6</sub>Mg<sub>80.9</sub>Fe<sub>12.5</sub> with % mean deviation of Fe 2.8%. This composition is the second Mg-rich ureilite (Fig. 6). One ellipsoidal grain of pyroxene (0.40×0.25 mm in size) entirely enclosed in a large olivine crystal

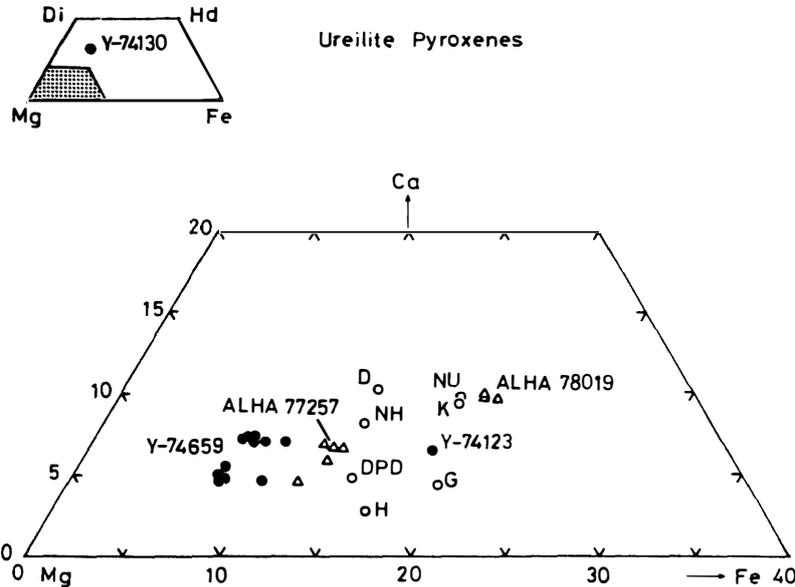
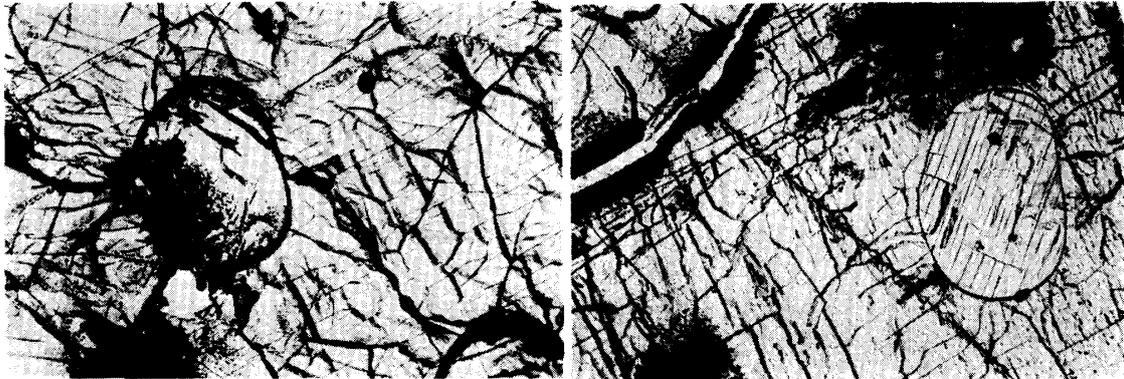


Fig. 6. Chemical compositions of ureilite pyroxenes plotted in a part of the pyroxene quadrilateral. Triangle: Allan Hills, filled: Yamato (Y) ureilites, open circle: others. Symbols and source are the same as those in Fig. 5. Mg-rich, low-Ca points are orthopyroxenes.

(Fig. 7) gives distinctly low Ca content (P 11-7 in Table 4). It shows cleavage-like fractures along the longest axis of ellipsoid and shows the straight extinction. The optical properties are not those of pigeonite but are compatible with those of orthopyroxene (T. ISHII, private communication). A similar pyroxene grain has been found in the Yamato-74659 ureilite. Both pyroxenes delineate the compositional gap of 2.5 mol. % Ca between the coexisting pair in orthopyroxene-pigeonite two-phase region. The pigeonite compositions vary from  $\text{Ca}_{7.3}\text{Mg}_{84.6}\text{Fe}_{8.1}$  to  $\text{Ca}_{6.7}\text{Mg}_{80.9}\text{Fe}_{12.4}$  and orthopyroxene from  $\text{Ca}_{4.5}\text{Mg}_{87.7}\text{Fe}_{7.8}$  to  $\text{Ca}_{4.4}\text{Mg}_{83.7}\text{Fe}_{11.9}$ . The orthopyroxene is more Mg-rich and Ca-poor. It is to be noted that no carbonaceous material was found between the orthopyroxene-like grain and the surrounding olivine.

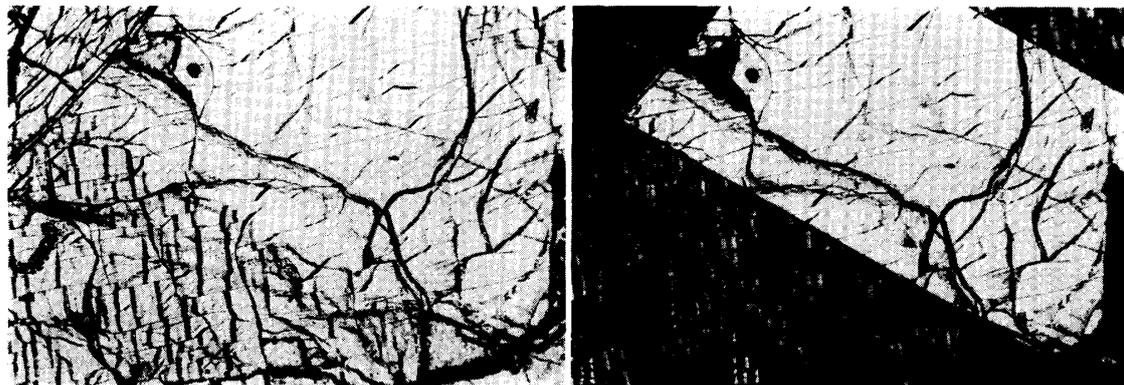
The ALHA78019 achondrite is another ureilite, consisting almost entirely of anhedral to subhedral olivine ( $\sim 90\%$ ) and pyroxene ( $\sim 5\%$ ). The olivine grains are fairly coarse-grained, ranging from 0.2 to 3.5 mm in diameter, and the pyroxenes 0.1 to 0.9 mm in the longest dimension. The rare pyroxenes are scattered evenly. Fractures, undulose extinction and polysynthetic twinning in the olivine and pyroxene grains are not as pronounced as in the other ureilite (Fig. 8). The grain boundaries are marked by a concentration of carbonaceous material. Only trace amounts of troilite and nickel-iron were observed in the grain boundaries.

Microprobe analyses show core compositions of olivine are uniform (average  $\text{Fa}_{23.5}$  with % mean deviation 0.7%, see Fig. 5). The magnesium enrichment near the grain boundary of the olivine characteristic of ureilite has been detected only



*a. Round olivine grain in pigeonite with carbonaceous materials in grain boundaries (open nicol).*

*b. Round orthopyroxene in olivine (open).*



*c. Fractured pigeonites with twin bands (open).*

*d. Pigeonites, the same as c (cross nicol).*

*Fig. 7. Photomicrographs of the ALHA77257 ureilite. Width: 0.95 mm.*



*a. Less fractured large pigeonite grain.*

*b. Round olivine grain with few fractures.*

*Fig. 8. Photomicrographs of the ALHA78019 ureilite. Width: 0.95 mm. Open.*

within about 10  $\mu\text{m}$  from the grain boundary. The pyroxene is a pigeonite with average composition (Table 4)  $\text{Ca}_{10}\text{Mg}_{71}\text{Fe}_{19}$ . These mafic minerals are among the most Fe-rich and Ca-rich ones in ureilites (Fig. 6).

The single-crystal X-ray diffraction patterns of olivine show very sharp unmisoriented spots, suggesting the shock effects are not strong.

### 3.5. *Primitive achondrite, ALHA77081*

This meteorite has been classified as intermediate between the H and E group chondrites and has some resemblance to Acapulco (MASON, 1978). PRINZ *et al.* (1980) argued for similarity to Winona and related meteorites and silicate inclusions in IAB irons, and proposed a primitive achondritic group.

ALHA77081 is coarse-grained, the largest mineral grain being little over 1 mm in diameter. The meteorite shows a recrystallized texture and is an olivine-pyroxene rock, with abundant metal and minor augite and plagioclase. The metal grains accompany troilite and chromite. The olivine and pyroxene grains include dust-like opaque mineral inclusions in their cores (Fig. 9).

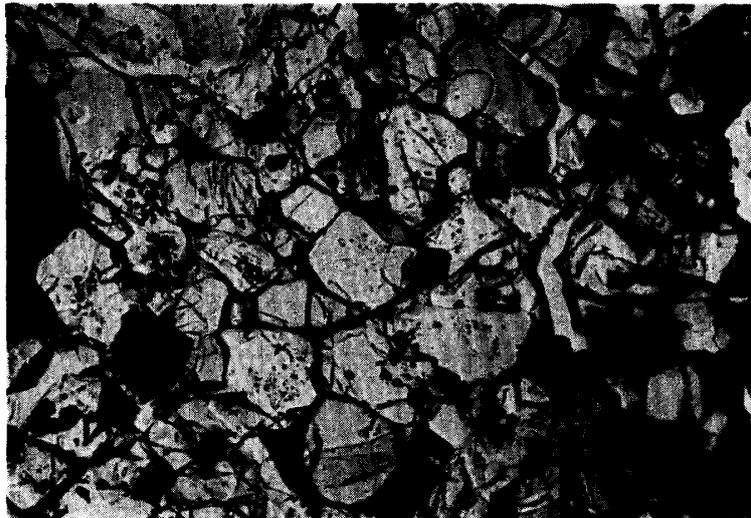


Fig. 9. Photomicrograph of ALHA77081, a primitive achondrite with olivine, orthopyroxene, augite, plagioclase, and opaques. Width: 0.95 mm. Open.

The chemical composition of olivine (Table 3) is similar to that of Yamato-74659 (ureilite), but amounts of minor elements such as CaO and  $\text{Cr}_2\text{O}_3$  are very small, and the MnO content is high. The presence of coexisting chromite and a large amount of metal, and the relatively low temperature of crystallization of ALHA77081 in comparison with ureilite, may be responsible for the differences. The metal grains have uniform compositions (Fe 93.2, Ni 6.6, Co 0.7 wt%). Some minute grains attached to the large Fe-rich grain or coexisting with troilite have

Table 5. Representative pyroxene composition (wt%) of ALHA77081.

Anal. No.	Opx Ph 7	Opx Ph 19	Aug Ph 19	Opx Ph 23	Aug Ph 21
SiO <sub>2</sub>	55.5	57.1	53.2	57.1	54.2
Al <sub>2</sub> O <sub>3</sub>	0.28	0.31	0.89	0.27	0.86
TiO <sub>2</sub>	0.22	0.23	0.57	0.21	0.57
Cr <sub>2</sub> O <sub>3</sub>	0.22	0.29	1.39	0.28	1.46
FeO	6.67	6.46	2.46	6.54	2.74
MnO	0.58	0.56	0.32	0.53	0.31
MgO	34.3	33.7	17.74	34.2	17.96
CaO	0.56	1.08	21.8	0.61	21.1
Na <sub>2</sub> O	0.03	0.03	0.75	0.01	0.75
Total	98.36	99.76	99.12	99.75	99.95
Cations (Oxygen=6)					
Si	1.960	1.983	1.954	1.982	1.971
Al (IV)	0.012	0.013	0.039	0.011	0.029
Al (VI)	0.000	0.000	0.000	0.000	0.008
Ti	0.006	0.006	0.016	0.005	0.016
Cr	0.006	0.008	0.040	0.008	0.042
Fe	0.197	0.188	0.076	0.190	0.083
Mn	0.017	0.016	0.010	0.016	0.010
Mg	1.805	1.745	0.971	1.769	0.968
Ca	0.021	0.040	0.858	0.023	0.822
Na	0.002	0.002	0.053	0.001	0.053
Total	4.026	4.001	4.017	4.005	4.002
Ca*	1.0	2.0	45.0	1.1	43.9
Mg	89.2	88.4	51.0	89.3	51.7
Fe	9.7	9.5	4.0	9.6	4.4

\* Atomic percent.

high Ni contents (Fe 49.2, Ni 50.4, Co 0.12 wt%). Only one grain in the thin section exhibited Widmanstätten pattern.

Orthopyroxene and augite coexist in this meteorite (Table 5) but are rarely in contact. The temperature of the last equilibration estimated by the pyroxene geothermometer (ISHII *et al.*, 1979) is between 985°C to 1070°C, the difference being due to the slight chemical zoning in the augites. The middle of the grain has lower Ca content than the rim. The Na<sub>2</sub>O and Cr<sub>2</sub>O<sub>3</sub> contents are significantly higher than those of chondrites. The MnO content of the orthopyroxene is high among the achondrites. The concentration of MnO is more enhanced in chromite, which con-

Table 6. Representative chemical compositions (wt%) of plagioclases and chromite in ALHA78006, 5 and ALHA77081.

Samples	Plagioclases			Chromite
	ALHA78006		ALHA77081	ALHA77081
	Ophit.	Clast	Ph 19	Ph 8
SiO <sub>2</sub>	44.9	44.9	64.5	0.00
Al <sub>2</sub> O <sub>3</sub>	33.4	35.2	22.4	6.16
TiO <sub>2</sub>	0.01	0.00	0.05	1.20
Cr <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	61.5
FeO	0.26	0.20	0.17	21.2
MnO	0.00	0.00	0.00	2.46
MgO	0.02	0.04	0.03	6.21
CaO	18.14	18.76	3.10	0.00
Na <sub>2</sub> O	1.26	0.67	9.35	0.06
K <sub>2</sub> O	0.08	0.02	0.75	0.00
Total	98.07	99.79	100.35	99.62*
Cations	O = 8			O = 24
Si	2.115	2.075	2.840	0.000
Al	1.855	1.919	1.162	1.518
Ti	0.000	0.000	0.002	0.189
Cr	0.000	0.000	0.000	10.168
Fe	0.010	0.008	0.006	3.709
Mn	0.000	0.000	0.000	0.436
Mg	0.001	0.003	0.002	1.935
Ca	0.915	0.929	0.146	0.000
Na	0.115	0.060	0.799	0.024
K	0.005	0.001	0.042	0.000
Total	5.016	4.995	4.999	17.979
Atomic %	K	0.1	4.3	
	Na	6.1	80.9	
	Ca	93.8	14.8	

\* ZnO: 0.83 wt%.

tains MnO up to 2.46 wt%. The chromite composition is high in Cr<sub>2</sub>O<sub>3</sub> and FeO contents and is close to those of iron meteorites (Table 6).

One pale green augite crystal up to 0.5 mm in the longest dimension gave the single crystal X-ray diffraction pattern of the C2/c symmetry, but minor reflections of pigeonite, P2<sub>1</sub>/c are detected. The diffraction spots are very sharp.

#### 4. Discussion

##### 4.1. Origin of the howardite parent body

New findings of polymict eucrites, polymict breccias of eucritic composition (Table 7) or howardites without diagenetic components have been one of the contributions of the recoveries of a large number of meteorites from Antarctica. The presence of a variety of eucritic components such as the Pasamonte-type, the Juvinas-type and a cumulate eucrite of the Moama type in these polymict eucrites in various proportion has given a strong support of a possible existence of the layered crust model of the howardite parent body proposed by us (TAKEDA, 1979). The polymict eucrites have been interpreted to be lithified regoliths produced by impacts of various-sized meteorites, that is, various depths of excavation of the layered crust. In spite of the variety of eucritic components, their bulk chemistries are essentially those of eucrites (Table 7). Some polymict eucrites are slightly rich in the diagenetic components. However, there have been a number of missing evidences, which can be

Table 7. Bulk chemical composition of polymict eucrites.\*

Samples	Yamato-74159	Yamato-75015	ALHA76005***	ALHA78132
SiO <sub>2</sub>	49.04	48.12	48.21	47.67
TiO <sub>2</sub>	1.09	0.73	0.78	0.62
Al <sub>2</sub> O <sub>3</sub>	10.35	12.65	12.02	12.40
FeO	19.23	17.96	18.89	17.93
MnO	0.53	(0.51)	0.52	0.49
MgO	8.29	8.15	7.66	8.80
CaO	9.48	9.53	9.08	9.09
Na <sub>2</sub> O	0.58	0.39	0.56	0.43
K <sub>2</sub> O	0.07	0.07	0.06	0.05
H <sub>2</sub> O(-)	0.00	—	0.27	0.20
H <sub>2</sub> O(+)**	0.32	—	1.1	1.38
P <sub>2</sub> O <sub>5</sub>	0.07	—	0.10	0.23
Cr <sub>2</sub> O <sub>3</sub>	0.44	0.37	0.40	0.44
FeS	0.15	—	0.17	
NiO	0.003	—	0.011	
Ni	—	—	—	0.0053
Co	0.003	—	0.003	<0.003
Total	99.65	98.48	99.83	99.73

\* Analysis by H. HARAMURA, except Yamato-75015 (TAKEDA *et al.*, 1979).

\*\* H<sub>2</sub>O+volatiles.

\*\*\* Allan Hills-765.

expected from the proposed origin.

The discovery of the ALHA78006 achondrite answers some of the questions raised by our previous study. First, partly inverted pigeonites with coarse exsolution lamellae of augite with (001) in common with the host found in Moore County (MC) have not been identified in the polymict eucrites. Only the inverted pigeonites of the Moama-type and uninverted pigeonites with coarse exsolution lamellae have been identified as cumulate eucrite component in Yamato-75011 and -75015 (TAKEDA *et al.*, 1979a). Now, the MC-type inverted pigeonites have been found to be an abundant component of ALHA78006.

Secondly, the presence of a very small amount of diogenitic orthopyroxene in ALHA78006 gives strong support on a genetic link between diogenites and eucrites. If the diogenitic mantle is present below the cumulate-eucrite layer, a moderate meteorite impact may excavate only down to a very upper portion of the diogenitic mantle and the diogenitic pyroxene will be mixed in a breccia rich in eucrite components. All the howardites studied to date include a large amount of diogenites and a small amount of the JV-type clasts in the matrix. The distinction between howardites and polymict eucrites with diogenite components may rest on the detectable amount of diogenite. 10% diogenitic component may be used as the lowest limit for howardites. The diogenitic pyroxenes are so small in ALHA-78006 that this meteorite is essentially a polymict eucrite. There may be a local difference in the type of cumulate eucrites present on top of the diogenite layer, because only the MC-type pyroxene is present in ALHA78006, and only the Moama-type in Yamato-75015.

Lastly, our observation of the dislocation texture of ALHA 77256 suggests that this diogenitic parental mass experienced a high temperature, slow strain-rate deformation (creep-like process) followed by a low temperature, fast strain-rate deformation, probably a shock deformation by meteoritic impacts. The record of the creep-like process is in line with the deep-seated origin of diogenites (MORI and TAKEDA, 1980).

#### 4.2. *The anticorrelation of the MnO/FeO variation in ALHA77081 and equilibrated chondrites*

Similarity of ALHA77081 to Acapulco, which has mineral compositions intermediate between the E and H chondrites, has been pointed out by MASON (1979). PRINZ *et al.* (1980) pointed out that these two meteorites and related meteorites such as Winona, Mt. Morris, Pontlyfini, Tierra Blanca and silicate inclusions in IAB irons, form a primitive achondrite group. MAYEDA and CLAYTON (1980) showed that these meteorites have come from a similar oxygen reservoir. Nevertheless, these meteorites have some near-chondritic characteristics.

Modal and mineral compositions of ALHA77081 are similar to those of Winona, except the amount of plagioclase. Orthopyroxene (36%), olivine (32%)

and opaques (27%) are present in approximately equal amounts but the plagioclase (4%) is less abundant and augite more abundant (3%) than in Winona. About 14 to 20% plagioclase is present in Winona and Mt. Morris. The compositions of plagioclase in ALHA77081 plot close to one of the clustered compositions  $K_{4.3}Na_{80.9}Ca_{14.8}$  of Yamato-74160, which is also an extensively recrystallized achondritic meteorite with a chondritic composition (LL7) (Fig. 10).

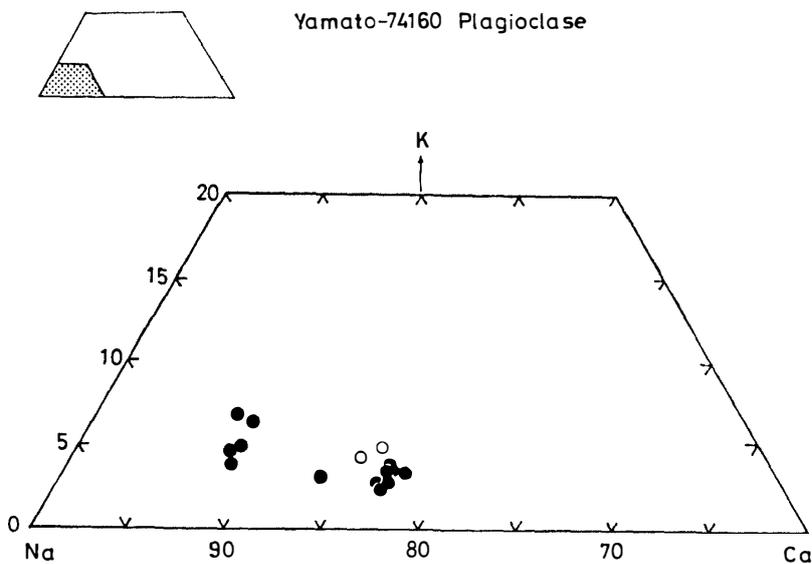


Fig. 10. Compositions of pair plagioclases in extensively equilibrated meteorites. Shaded area is enlarged. Filled circle: Yamato-74160, LL7, open circle: ALHA77081.

Assuming that ALHA77081 is a chondrite, we can compare the MnO/FeO ratio with those of equilibrated chondrites and of Yamato-74160 (Fig. 11). In Fig. 11 we show that the MnO/FeO ratios in the type 6 chondrites increase with decreasing FeO content of pyroxene. The same plots for an unequilibrated chondrite scatter around the H6-LL6 trend. The following mechanism has been proposed to produce the observed anticorrelation of the MnO/FeO variation (TAKEDA, 1980). For those unequilibrated pyroxenes, which were equilibrated in the H chondrite environment, most of the Fe ions will be reduced to metal and migrate into the nickel-iron phase, resulting in relative enrichment of Mn in the pyroxenes, because Mn is not a siderophile ion. For those pyroxenes equilibrated in the LL chondrite environment, Fe in the metal phase is oxidized and will migrate into the pyroxenes, resulting in relative enrichment of Fe in the pyroxenes, and of Ni in the metal phase.

If the above mechanism is in effect, it is anticipated that for more reduced meteorites than the H-type, more enrichment of Mn in pyroxene may take place. The MnO/FeO value of ALHA77081 obtained by our study exactly follows this

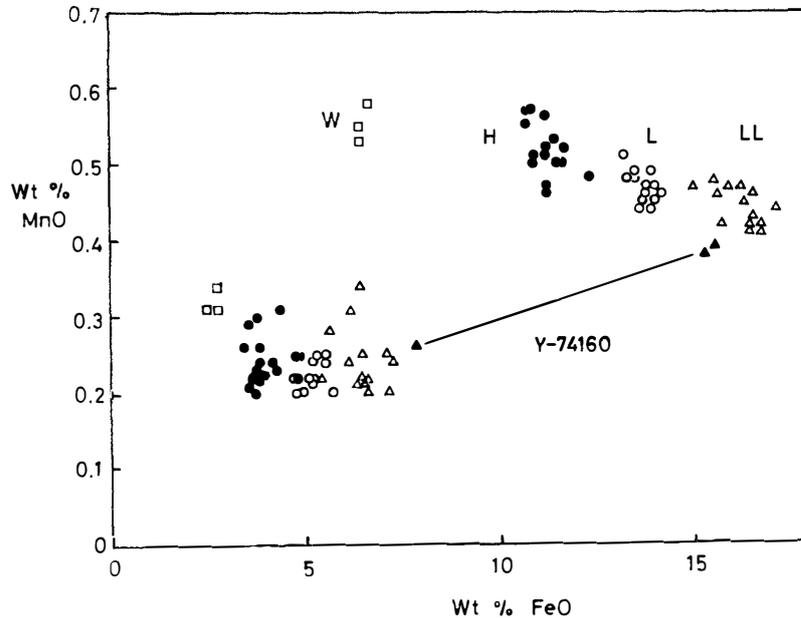


Fig. 11.  $MnO/FeO$  variation diagram showing negative slope for pyroxenes in equilibrated chondrites (H, L, LL) and ALHA77081 (W). Upper group: orthopyroxene; lower group: augite. Data of the chondrites after BUNCH and OLSEN (1973).

trend, although this meteorite may not be a chondrite. The Mn ion is even more concentrated in the coexisting chromite.

The  $MnO/FeO$  correlation is well known for the lunar and the howarditic pyroxenes (DYMEK *et al.*, 1976). This trend will be produced whenever the Mn/Fe fractionation takes place between the liquid and the solid. The anticorrelation observed in the chondrites and ALHA77081 is the result of reequilibration in the solid state when the metal is involved. The enrichment of Mn in radial pyroxene chondrules was interpreted to have been produced in the condensation process in the solar nebula (MCSWEEN, 1979). The behavior of the Mn ion will be useful in interpreting similar phenomena in the ureilite parent body.

#### 4.3. Origin and evolution of the ureilite parent body

The new findings of five Antarctic ureilites, some of which have extreme chemical compositions, have enabled us to test some of the hypotheses proposed for the origin of ureilites. By the discovery of Mg-rich ureilites Yamato-74659 and ALHA-77257, and the Fe-rich one ALHA78019, the chemical range of the ureilite pyroxenes is further extended in the Mg-Fe direction, except Yamato-74130 which contains augite. Before these discoveries, the  $MnO/FeO$  plots were scattered. Now the new plots in Fig. 12 indicate subtle anticorrelation. At least, non-positive correlation of the ureilite trends may discriminate some of the origins involving liquid-solid fractionation.

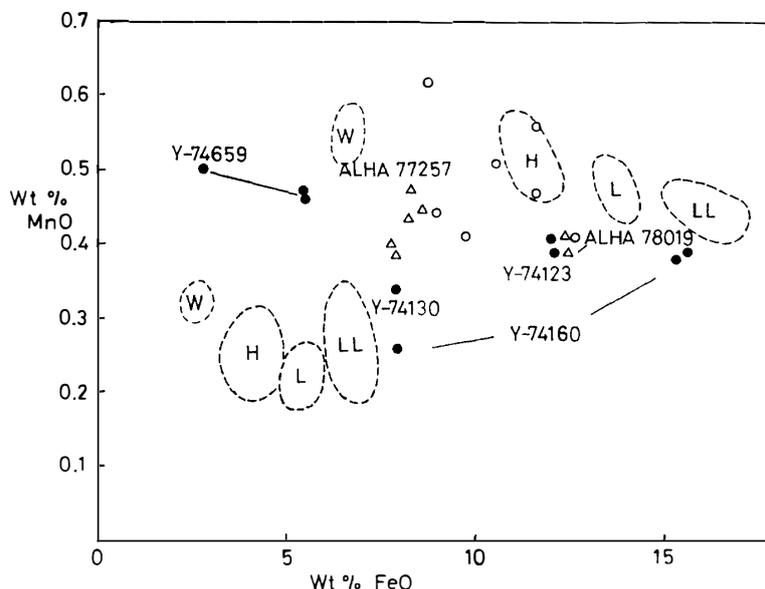


Fig. 12. *MnO/FeO* variation diagram for the ureilite pyroxenes. The data in Fig. 11 is copied by dotted circles. Triangle: Allan Hills, filled circle: Yamato, and other data after BERKLEY *et al.* (1978).

The ureilites have been suggested to have formed (1) by shock recrystallization of carbonaceous chondrites (VDOVKIN, 1970), (2) as residues of partial melting (WLOTZKA, 1972; BOYNTON *et al.*, 1976), and (3) as cumulates, ultramafic rocks (BERKLEY *et al.*, 1976) as was summarized by BERKLEY *et al.* (1978); and (4) by a process involving fragmentation of a small planetesimal of loosely compacted mixtures of olivine and pyroxenes and carbonaceous materials sedimented from the solar nebula. Process (4) cannot be rejected on the basis of the data presently available (TAKEDA and YANAI, 1978). If the anticorrelation of the MnO/FeO variation is real, hypotheses (2) and (3) may not be supported strongly, because the processes include the liquid/solid fractionation, otherwise metal fractionation might have taken place at the time of crystallization. However, such separated metal has not been detected in any ureilite.

Evenly distributed carbon around crystals, and easy separation of single crystals from the mass are not good evidence to support the crystallization from liquid. The difference in density between carbon and silicates is large enough to make distribution uneven. An idea that carbon was injected into the rock, possibly during the shock event is opposed by the fact that carbon has not penetrated into fractures produced by the shock event. The nickel-iron in mesosiderites, for which an evidence of the shock metamorphism has been recognized (FLORAN *et al.*, 1978), fills fine fractures of orthopyroxenes. Mixing of early crystallized silicate crystals and later condensed carbon and compaction of the carbon-coated crystals in a loosely packed planetes-

imal may be an equally acceptable model as the above hypotheses.

The presence of a less shocked ureilite, ALHA78019, poses a problem to produce high shock pressure which converted carbon into diamond. Collision of loosely packed planetesimals may account for the observation, because shock between the grain boundaries is expected to be higher than within the grains. This model also explains the retention of planetary-type noble gases in diamond (GÖBEL *et al.*, 1978). Absorbed gases in a loosely packed planetesimal will be fixed in shock-produced diamond by a collision, and will not be expelled by a later high-temperature metamorphic event.

The triple-points junctures and curved grain boundaries common in ureilites indicate a thermal metamorphism. The temperature of this event as high as 1230°C for Yamato-74659 has been estimated from the pigeonite geothermometer of ISHII (1975). Our new findings of a pigeonite-orthopyroxene pair in the two-pyroxene region in Mg-rich ureilites suggest even higher temperature than the above. The high Ca content in olivine is also a good indication of high temperature annealing. No provable heat source has been proposed for this event, because the Al contents of ureilites are not high.

In spite of very uniform compositions and coarse-grained textures produced at very high temperature, neither exsolution of augite nor inversion to orthopyroxene has been detected in the ureilite pyroxenes. Other achondritic or terrestrial pigeonites with such plutonic textures as were observed in ureilites were all inverted to orthopyroxenes with coarse exsolution lamellae of augite by slow cooling through 1100°C to 900°C. Even pigeonites in lunar mare basalts, which were cooled rapidly, show fine augite exsolution detectable by the X-ray method. The lack of such exsolution suggests a break-up of a planetesimal by a collision that produced shock effects in ureilites.

In the light of our data on a variety of pyroxene compositions in the newly found Antarctic ureilites, the origin and evolution of ureilites may be constrained to some extent. The occurrence of augite in Yamato-74130, which contains olivines as Fe-rich as that of ALHA78019, and a very Mg-rich pigeonite in Yamato-74659 may not be consistent with the idea that ureilites represent cumulates differentiated from a common magma source.

A cumulate-type preferred orientation of olivines in Novo Urei and Kenna observed by universal stage mineral orientation studies (BERKLEY *et al.*, 1976, 1978) may be equally well produced by sedimentation of olivine crystals towards the equator of the solar nebula.

Several lines of evidence explained in the previous paragraphs point towards a model of the ureilite parent body or bodies not before expounded, and is consistent with the origin and evolution of the early solar nebula (SAFRONOV, 1969; HAYASHI *et al.*, 1977). Neither this nor existing models can be accepted or rejected unequivocally in the light of the current data, but the following model may be worthwhile

testing by other evidence.

Silicate grains grew in the solar disk and were sedimented towards the equatorial plane of the disk to form a thin layer. Early-crystallized and sedimented olivine and pyroxene grains will be mixed with later-condensed carbonaceous materials. The difference in chemical composition may depend on the location in the solar disk, hence the oxidation-reduction conditions and separation of the metal phases. As soon as the density of the mineral layer became much greater than the certain limit, the mineral layer began to be fragmented into a number of planetesimals with the masses of the order of  $10^{18}$  g (SAFRONOV, 1969). At this stage, hot gases may be present so that the planetary gases were trapped by the loosely packed planetesimals, and stored the heat to equilibrate the mineral grains. By compaction of the body by its own gravity and occasional impacts of other bodies, some of the planetesimals grew into a ureilite parent body or into other protoplanet, and gases were trapped in the interior. The thermal annealing proceeded in the planetary interior. By a collision of a larger body, the planetesimal was fragmented into smaller masses, resulting in a rapid cooling from a near planetary interior condition.

#### *4.4. Achondrite parent bodies*

A number of polymict breccias (DUKE and SILVER, 1967) of eucritic compositions found in Antarctica enabled us to reconstruct their parent body or bodies. The howardite parent body (MASON, 1962, 1967; TAKEDA, 1979) thus derived is a body large enough to melt the outer thin crust, to produce a differentiated layered crust and to retain regolith produced by impacts of various scale. The unique achondrites such as ALHA77005 and ALHA77081 reveal an existence of thermalized small primitive planets in the solar system other than the howardite parent body. The ureilite parent-body model postulated from our studies on unusual ureilites is consistent with a planetesimal which existed in the early evolution of the solar disk.

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