ANTARCTIC HOWARDITES AND THEIR PRIMITIVE CRUST

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Abstract: Lithic clasts and mineral fragments in Yamato-79 howardites, Y-790727, Y-791208 and Y-791492 have been investigated by optical microscopy, electron microprobe and single crystal X-ray diffraction. These howardites are chemically intermediate between ordinary diogenites and eucrites, and distinct from Y-7308. Some lithic clasts are also intermediate in mineralogy between endmember diogenites and eucrites, including a cumulate eucrite clast with a partly inverted pigeonite, an ordinary eucrite-like gabbroic clast intermediate in chemical composition between cumulate eucrites and ordinary eucrities, and an augite rich clast with a silica mineral. A partial melting model and fractional crystallization models have been compared to account for these new howardites, and models involving two-stage process are proposed. These howardites may have been products of excavation by an impact or impacts shallower than that for Y-7308 but deeper than those for polymict eucrites.

1. Introduction

Howardites are polymict breccias, that contain a series of mineral and lithic fragments covering a range of rock types similar to diogenites, cumulate eucrites and ordinary eucrites, and olivine fragments (DUKE and SILVER, 1967; MASON *et al.*, 1979). Because howardites, eucrites and diogenites are suites of closely related meteorites, we proposed that these meteorites be called HED achondrites (TAKEDA *et al.*, 1983). It was proposed that the HED achondrites developed on the same parent body (CONSOLMAGNO and DRAKE, 1977; TAKEDA *et al.*, 1976), and they have been used for model reconstruction of the layered crust of their parent body (TAKEDA, 1979).

Although a large number of Antarctic HED achondrite specimens have been recovered, howardites are rare (TAKEDA *et al.*, 1983) and polymict eucrites are common in the Antarctic collection (TAKEDA *et al.*, 1983). Yamato-7308 was the only one true howardite in the Antarctic meteorite collection until the discovery of several howardites in 1979 by the Japanese Antarctic Research Expedition (JARE) (TAKEDA and YANAI, 1982). Two howardites from Victoria Land, ALHA78006 and EETA79006 (SCORE *et al.*, 1982) have been reclassified as polymict eucrites using the criterion of DELANEY *et al.* (1983b). Detailed description of Y-7308 and its origin are given by IKEDA and TAKEDA (1984), TAKEDA *et al.* (1976) and YAGI *et al.* (1978)

The howardite meteorites have been interpreted to be lithified ejecta deposited by impacts of various sized meteorites and hence sample various depths of excavation of the crust on their parent body. The study of howardites provides us with information of a variety of components, such as diogenites and eucrites, and their genetic relationship. We investigated howardite-like specimens listed in "Tentative Catalog of Yamato Meteorites" compiled by YANAI (1983), as a part of the preliminary examination of the Yamato-79 collection.

The results were interpreted to constrain a crystal fractionation model (MASON, 1962; MCCARTHY *et al.*, 1973; DELANEY *et al.*, 1981) for the origin of howardites proposed recently on the basis of the Y-7308 howardites by IKEDA and TAKEDA (1984). Yamato-79 howardites contain rock fragments, that have not been described previously, and contribute to further evidence that can be used to reconstruct their parent body, and to help deduce their origin and evolution. We have also compared these true howardites with other Antarctic achondrites, and propose two stage models involving both partial melting (STOLPER, 1977) and crystal fractionation.

2. Samples and Experimental Techniques

Yamato-790727 (120.4 g), -791208 (47.9 g) and -791492 (41.1 g) are three howardites tentatively identified in the Y-79 collection. Three polished thin sections supplied by the National Institute of Polar Research (NIPR) have been examined by optical microscope and microprobe. Physical descriptions of two other howardites, Y-791074 and -791206 are also given.

Chemical analyses were carried out on two electron microprobes. Chemical zoning and phases unmixed by exsolution in pyroxenes were examined by measuring the Ca, Mg and Fe concentrations by scanning or at 5 to 50 μm intervals, with a JEOL JXA-5 electron-probe X-ray microanalyzer with a 40° take-off angle. Quantitative chemical analyses were made with a JEOL 733 Super Probe at the Ocean Research Institute of the University of Tokyo and at NIPR, by employing the same parameters as those used with the JXA-5. The method is the same as that of NAKAMURA and KUSHIRO (1970).

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

3. Results

3.1. Y-790727

This specimen was originally listed as a polymict eucrite in the first catalog of the Yamato-79 collection (KOJIMA and YANAI, 1981), but greenish yellow pyroxenes exposed on the surface of the specimen were confirmed to be orthopyroxene of the howardite-type by single crystal X-ray diffraction. The bulk chemical compositions (Table 1) analyzed by H. HARAMURA plot in the middle of the diogenite-eucrite trend in the Al_2O_3 *vs.* CaO diagram (Fig. 1), and is close to that of cumulate eucrite, Binda.

This is an angular stone covered by black shiny fusion crust. Irregular deep pits are distributed unevenly, where a slightly stained gray matrix of fine mineral fragments can be seen. At the bottom of a large hole, a relatively coarse lithic clast is observed. Similar vugs have been described in Allan Hills collections (SCORE *et al.*, 1982).

Table 1. The bulk chemical composition of Yamato diogenites and cumulate eucrites, howardites and a eucrite (Analyses by H. HARAMURA, private comm., 1983). Data of Y-7308 is after M. SHIMA (YAGI et al., 1978).

No.	Y-7308	Y-791000	Y-791199	Y-791200	Y-791422	Y-790727	Y-791208	Y-791492
SiO_2	51.06	51.50	51.41	51.30	51.62	48.79	49.38	49.56
TiO_2	0.22	0.30	0.18	0.30	0.26	0.38	0.26	0.34
Al_2O_3	3.64	1.59	1.45	2.84	2.99	7.66	6.38	6.51
Fe_2O_3		1.50	1.65	0.0	0.26	2.87	2.32	5.35
FeO	16.00	18.32	18.05	18.48	18.31	13.69	14.75	11.85
MnO	0.57	0.64	0.64	0.58	0.56	0.49	0.49	0.53
MgO	22.02	21.40	21.93	21.81	21.05	17.65	18.32	17.55
CaO	3.50	3.26	2.97	3.25	3.51	5.76	4.89	5.74
Na_2O	0.16	0.07	0.10	0.13	0.21	0.21	0.18	0.21
K_2O	0.06	0.03	0.04	0.04	0.03	0.02	0.02	0.03
$H_2O(-)$		0.03	0.00	0.00	0.03	0.27	0.32	0.20
$H_2O(+)$		1.20	0.66	0.41	0.3	0.85	1.58	0.93
P_2O_5	0.01	0.08	0.08	0.15	0.03	0.15	0.07	0.07
Cr_2O_3	0.68	0.70	0.80	0.65	0.63	0.75	0.85	0.80
FeS	0.75		0.67	0.52	0.56	0.77	0.30	0.82
Fe	0.39							
Ni*		0.0028	0.0052	0.0072	0.021		0.04	0.019
Total	99.09	100.62	100.63	100.46	100.37	100.31	100.15	100.50

*NiO: Y-790727 239 ppm.

The thin section shows complex breccia of angular fragments, up to 1.7 mm long, of orthopyroxene, inverted pigeonite, pigeonite, olivine, and plagioclase, with a few lithic clasts, set in a matrix of comminuted pyroxene, olivine and plagioclase. This texture and mineralogy is typical of howardites. Accessory chromite and ilmenite and trace amounts of troilite and nickel-iron are present. The lithic clasts are holocrystalline orthopyroxenite and pyroxene-plagioclase aggregates, and range in texture from dunite, coarse-grained orthopyroxenitic and gabbroic to fine-grained basaltic types. Dark aphanitic clasts are also present.

Microprobe analyses show a wide range in pyroxene composition as is shown in

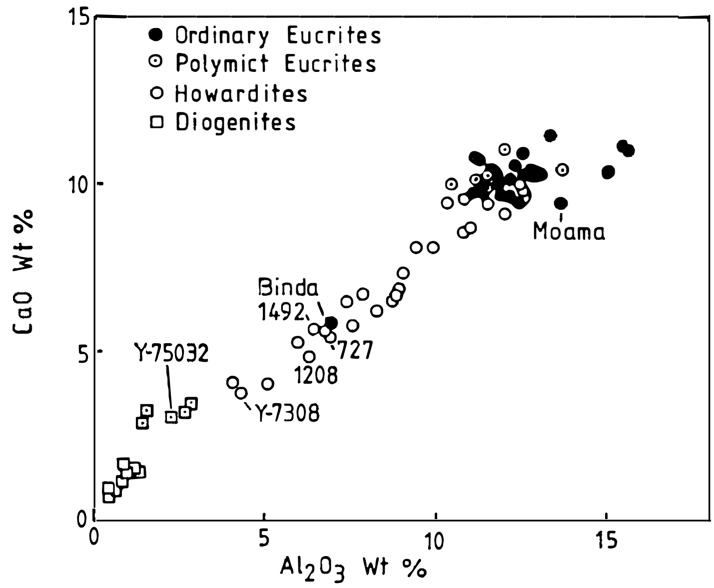


Fig. 1. Plot of CaO against Al_2O_3 (wt %) for the HED achondrites. Data after MASON et al. (1979), FREDRIKSSON et al. (1976) and analyses by H. HARAMURA (Table 1).

Fig. 2. Pyroxenes (Table 2) similar in composition to those in diogenite and eucrites are common, but some pyroxene compositions extend beyond the most Mg-rich diogenite to nearly $Ca_1Mg_{81}Fe_{17}$ (Frag. Opx in Table 2), and there are inverted pigeonites with Fe/(Mg+Fe) between 0.3 to 0.6. The olivine compositions (Table 3) range from Fa_{11} to Fa_{29}. Plagioclase ranges from An_{94} to An_{82} and averages An_{88} (Table 4 and Fig. 3). The presence of orthopyroxene has been confirmed by the single crystal X-ray diffraction.

The largest clast (GD7) in the thin section, 1.7×1.4 mm in size, shows a fine-grained granoblastic texture of orthopyroxene (Fig. 4a) and includes minor fine chromite grains. The texture is similar to some portions of the Y-74013-type diogenites with granoblastic texture. Another recrystallized orthopyroxenite clast (RD7) 0.8×0.7 mm in size, contains very fine rectangular to lath shaped crystals, but there remains in one area, an unrecrystallized coarse orthopyroxene crystal (Fig. 4b). No olivine was present. The fine texture suggests a part of orthopyroxene was molten and cooled rapidly to produce the fine-grained texture. More Mg-rich compositions of the melted portion (Table 2) is in agreement with this interpretation.

A basaltic clast 0.53×0.36 mm in size consists of slightly radiating subparallel laths of alternating pigeonite and plagioclase (Fig. 4c). The pyroxenes with the eucritic composition show augite exsolution with (001) in common with the host.

3.2. Y-791074

An oblong stone covered with rough surfaces and 20% dull black fusion crust. There are few pits and spots of oxidation stain on the broken surfaces. Three major fracture systems penetrate into the interior. Matrix is fine-grained gray with spots of very small opaques. Clast types include a pale yellow pyroxene-rich clast 7×3.5 mm in size with very little white plagioclases, pale greenish yellow, pale to dark brownish

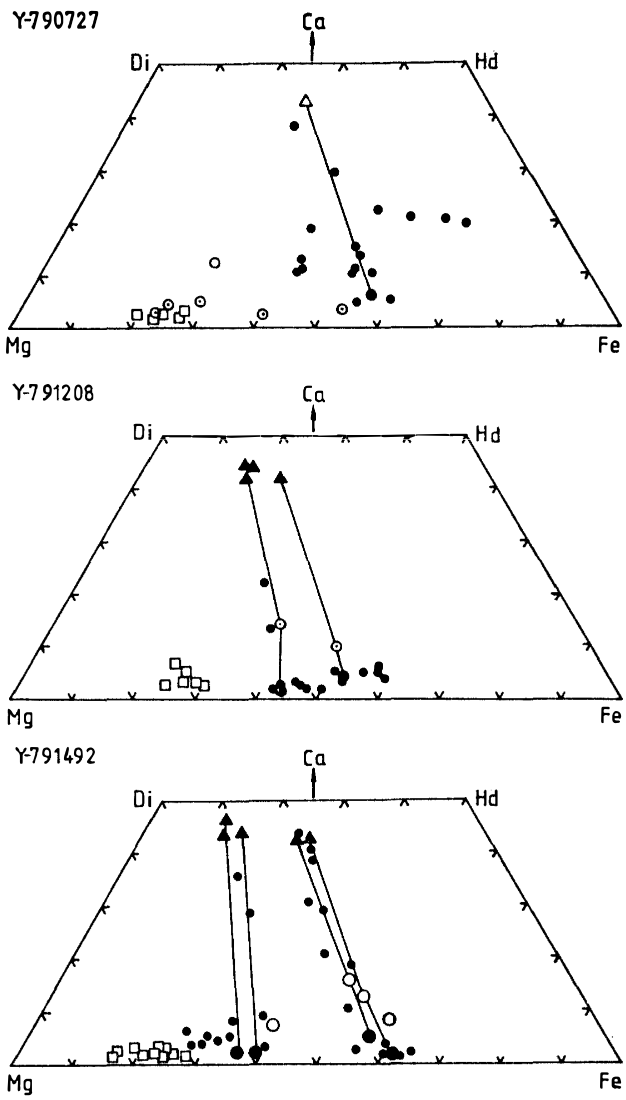


Fig. 2. Pyroxene quadrilateral of the Yamato-79 howardites. Square: diogenitic orthopyroxenes, open circle with dot: bulk composition of inverted pigeonite, solid circle: host or bulk composition of pigeonite and triangle: augite lamellae. The tie line connects the lamella-host pair.

gray pyroxene fragments, a eucritic clast with reddish brown pyroxenes, and plagioclase fragments. No thin section is available for this study, but it was studied by DELANEY *et al.* (1984).

3.3. Y-791186

A complete slightly brecciated eucrite with subround pyramidal shape, is covered with thin black fusion crusts except two broken portions (top and one side). Areas devoid of fusion crust show subophitic to granular textures with brownish gray pyroxene (0.2 to 1 mm in length) and white plagioclase. The largest pyroxene crystal reaches up to 3 mm in diameter. Spots of oxidation stain distribute less frequently.

A thin section made from a surface of one side is reported to contain orthopyroxene fragments (DELANEY *et al.*, 1984), but another thin section made from a large chip of

Table 2. Selected pyroxene compositions (wt %) of mineral fragments and lithic clasts in Y-790727.

Remarks	Frag. Opx Mg-rich	Diog.-clast, RD Opx remelt.	Diog.-clast, RD Opx unmelt.	Frag. Opx cum.Euc	Frag. Aug Fe-rich	Euc-clast Pig host	Euc-clast Aug lamella	Frag. Aug lamella
SiO_2	55.61	55.61	54.12	52.06	47.84	49.40	50.45	49.98
Al_2O_3	0.64	0.68	1.38	0.43	0.82	0.72	1.55	0.84
TiO_2	0.05	0.09	0.06	0.27	0.84	0.53	1.05	0.32
Cr_2O_3	0.41	1.04	0.79	0.23	0.12	0.20	0.64	1.57
MgO	30.13	29.79	28.14	20.05	4.73	13.67	11.14	12.60
FeO	11.70	11.24	12.87	24.39	34.78	31.37	14.55	21.88
MnO	0.43	0.42	0.47	0.68	0.98	0.89	0.69	0.79
CaO	0.82	1.00	1.44	1.31	9.29	2.84	18.86	11.70
Na_2O	0.00	0.02	0.01	0.00	0.05	0.11	0.11	0.07
Total	99.81	99.88	99.30	99.48	99.48	99.79	99.03	99.74
Si*	1.976	1.974	1.952	1.979	1.972	1.954	1.945	1.946
Al	0.027	0.028	0.059	0.019	0.040	0.033	0.070	0.038
Ti	0.001	0.002	0.002	0.008	0.026	0.016	0.030	0.009
Cr	0.011	0.029	0.023	0.007	0.004	0.006	0.019	0.048
Mg	1.596	1.576	1.513	1.136	0.291	0.806	0.640	0.731
Fe	0.348	0.334	0.388	0.775	1.199	1.038	0.469	0.712
Mn	0.013	0.013	0.014	0.022	0.034	0.030	0.022	0.026
Ca	0.031	0.038	0.056	0.053	0.410	0.120	0.779	0.488
Na	0.000	0.001	0.001	0.000	0.004	0.008	0.008	0.005
Total	4.004	3.995	4.006	4.002	3.982	4.005	3.984	4.004
Ca**	1.6	2.0	2.8	2.7	21.6	6.1	41.2	25.3
Mg	80.8	80.9	77.3	57.8	15.3	41.0	33.9	37.9
Fe	17.6	17.1	19.8	39.5	63.1	52.8	24.8	36.9

*Cations per six oxygens.
**Atomic per cent.

the other side shows that it is a monomict eucrite with partly inverted pigeonite. The presence of orthopyroxene would imply that it is a howardite, or a polymict eucrite with little orthopyroxene. However, the orthopyroxene fragment could be derived from the core of the inverted pigeonite.

3.4. Y-791206

This nearly conical stone contains two broken surfaces and three faces covered with thin black dull fusion crusts. Areas devoid of fusion crust are pitted. Many round pits are present, some of which have the depth deeper than the diameter. Pyroxene clasts (1–3 mm) ranging from pale yellow, light to dark green are set in a fine-grained gray matrix. A fine-grained ophitic eucrite clast 6 mm in diameter was found at the wall of a pit. Similar to Y-790727. This specimen is being kept intact for future study.

3.5. Y-791208

An oblong stone is covered with dull black fusion crusts and rounded shiny black patches, but both elongated sides are broken and heavily pitted, leaving the wall adjacent to the fusion crust. It is oxidized, and outer 2 mm from the fusion crust has oxidation stain. Some rounded pits penetrate deep into the interior. This meteorite is rich in

Table 3. Selected chemical compositions (wt %) of olivine and chromite in Yamato howardites, Y-790727, -791208 and -791492.

Remarks	Olivine				Chromite			
	727	1208 Fe-rich	1208 Mg-rich	1492	1208	1492 L-clast	1492 Opx	1492 Ti-rich
SiO_2	38.23	36.43	40.18	38.15	0.01	0.01	0.15	0.14
Al_2O_3	0.07	0.00	0.06	0.01	16.95	7.72	10.21	9.95
TiO_2	0.00	0.02	0.01	0.00	0.96	0.45	0.27	3.47
Cr_2O_3	0.40	0.01	0.11	0.06	47.00	58.00	55.60	47.38
MgO	37.30	34.45	51.15	38.87	4.89	3.35	4.11	1.69
FeO	23.64	28.47	7.74	22.99	26.46	29.03	26.88	35.09
MnO	0.57	0.75	0.16	0.52	0.66	0.60	0.59	0.49
CaO	0.25	0.09	0.06	0.13	0.00	0.00	0.00	0.10
Na_2O	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Total	100.50	100.23	99.48	100.73	96.93	99.16	97.79	98.29
Si*	0.998	0.979	0.983	0.990	0.002	0.003	0.031	0.031
Al	0.002	0.000	0.002	0.000	4.092	1.933	2.537	2.520
Ti	0.000	0.000	0.000	0.000	0.148	0.072	0.043	0.560
Cr	0.008	0.000	0.002	0.001	7.613	9.748	9.272	8.052
Mg	1.452	1.380	1.865	1.504	1.495	1.060	1.293	0.540
Fe	0.516	0.640	0.158	0.499	4.533	5.161	4.741	6.308
Mn	0.013	0.017	0.003	0.011	0.115	0.107	0.104	0.089
Ca	0.007	0.003	0.002	0.004	0.000	0.000	0.001	0.023
Na	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000
Total	2.997	3.006	3.015	3.009	17.998	18.086	18.022	18.124
Fo**	73.8	68.3	92.2	75.1				
Fa	26.2	33.0	7.8	24.9				

*Cations per four oxygens for olivine and twenty four oxygens for chromite.
**Mole per cent.

pyroxene fragments (1–4 mm) with color from pale yellow, pale greenish yellow to dark brownish yellow, set in a fine-grained brecciated matrix. Plagioclase fragments and eucritic clasts are not common.

The thin section shows abundant lithic and mineral fragments similar to diogenites, cumulate eucrites, and eucrites. A considerable amount of weathering is indicated by large areas of rusty staining. Two large interesting lithic clasts were identified.

One clast (MC8), 1.2×0.9 mm in size, consists of a partly inverted pigeonite crystal texturally very similar to that in Nagaria (Fig. 5a) and a homogeneous plagioclase $Ab_{8.2}An_{91.5}Or_{0.3}$ (Table 4 and Fig. 3). The pyroxene has bulk chemical composition $Ca_{14}Mg_{50}Fe_{36}$ (Table 5), with exsolved augite lamellae up to 10 μm thick with (001) in common with the host. Thin augite lamellae on (100) are present in the host.

Another clast (GB8) 2.6×2.3 mm in size displays a gabbroic texture (Fig. 5b) with crystals of pigeonite and plagioclase (An_{90}). The pigeonite crystals have round outline and show clouding common in the ordinary eucrites and fine regular exsolution lamellae of augite on (001). These features are very similar to that of ordinary eucrites but the bulk chemical composition of the pyroxene $Ca_{12}Mg_{40}Fe_{48}$ (Table 5) is near the Mg-rich limit of the eucrites and is more Mg-rich than common eucrites such as

Table 4. Selected plagioclase compositions (wt %) of Y-790727, -791208 and -791492.

Remarks	Y-790727		Y-791208					Y-791492	
	An -rich	Ab -rich	Frag.	MC clast	GB clast	Frag.	Aphan. clast	An -rich	Frag.
SiO_2	45.37	46.11	46.26	44.98	45.30	47.25	48.64	43.74	45.37
Al_2O_3	34.43	34.15	33.32	35.36	35.24	34.14	33.84	36.31	34.95
TiO_2	0.00	0.00	0.00	0.02	0.04	0.02	0.03	0.00	0.00
Cr_2O_3	0.00	0.03	0.00	0.01	0.00	0.00	0.02	0.00	0.00
MgO	0.02	0.02	0.02	0.03	0.00	0.03	0.02	0.05	0.03
FeO	0.09	0.04	0.09	0.12	0.03	0.73	0.51	0.14	0.32
MnO	0.04	0.01	0.02	0.02	0.00	0.03	0.01	0.01	0.01
CaO	18.18	17.63	18.60	18.50	18.59	16.20	14.93	19.28	18.05
Na_2O	0.99	1.34	1.13	0.92	1.06	1.96	2.07	0.53	1.08
K_2O	0.09	0.10	0.03	0.05	0.06	0.13	0.09	0.02	0.04
Total	99.20	99.49	99.47	100.01	100.32	100.50	100.14	100.08	99.85
Si*	2.107	2.132	2.144	2.075	2.083	2.161	2.215	2.022	2.095
Al	1.885	1.861	1.820	1.923	1.910	1.840	1.816	1.978	1.902
Ti	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.000	0.000
Cr	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Mg	0.001	0.001	0.002	0.002	0.000	0.002	0.001	0.003	0.002
Fe	0.004	0.001	0.003	0.004	0.001	0.028	0.019	0.005	0.012
Mn	0.002	0.000	0.001	0.001	0.000	0.001	0.000	0.001	0.001
Ca	0.905	0.874	0.924	0.914	0.916	0.794	0.728	0.955	0.893
Na	0.089	0.120	0.102	0.082	0.095	0.174	0.182	0.047	0.097
K	0.005	0.006	0.002	0.003	0.004	0.008	0.005	0.001	0.002
Total	4.997	4.999	4.997	5.005	5.010	5.008	4.970	5.013	5.004
Ab**	8.9	12.0	9.9	8.2	9.3	17.8	19.9	4.7	9.7
An	90.6	87.4	89.9	91.5	90.3	81.4	79.5	95.2	90.0
Or	0.5	0.6	0.2	0.3	0.4	0.8	0.6	0.1	0.2

*Cations per eight oxygens.
**Mole per cent.

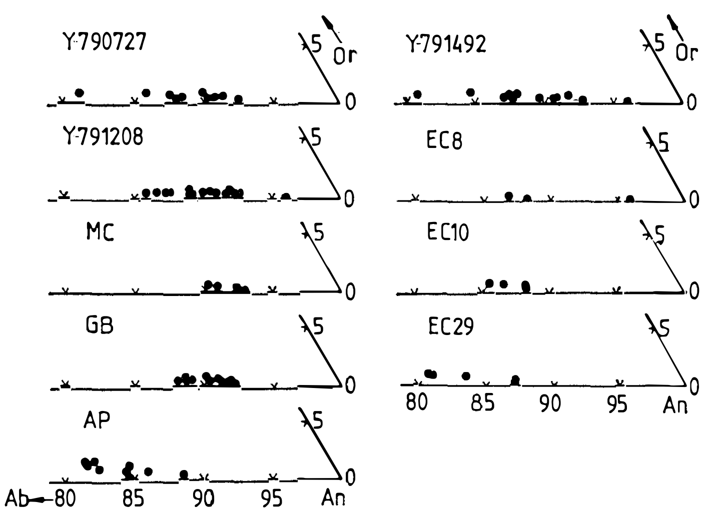


Fig. 3. Plagioclase compositions of the Yamato-79 howardites. Only anorthite (An)-rich portions of the Or-Ab-An diagrams are given. MC: Moore County like clast (MC8) in Y-791208, GB: gabbroic clast (GB8) in Y-791208, AP: Aphanitic clast with plagioclase fragments in Y-791208.

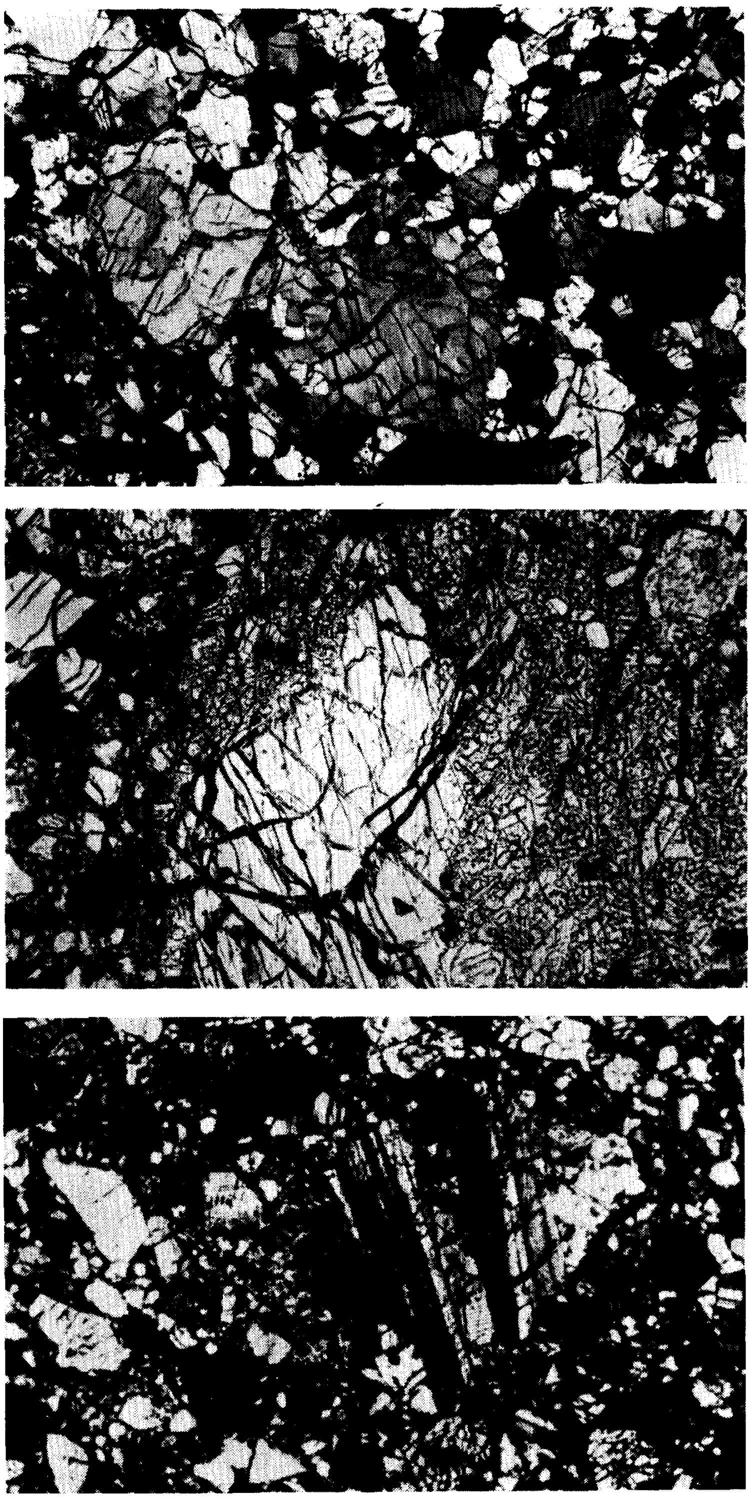


Fig. 4. Photomicrographs of lithic clasts in Y-790727.

a. Fine-grained granoblastic texture of orthopyroxene in a diogenitic clast (GD). Cross polarized light. Width 1.3 mm.

b. Partly shock melted and recrystallized diogenite clast (RD). Width 1.3 mm. Unpolarized light.

c. A round eucritic clast.

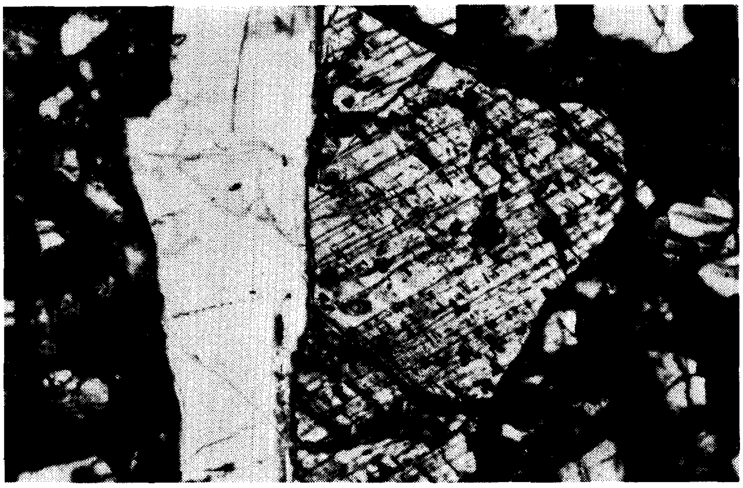


Fig. 5. Photomicrographs of lithic clasts in Y-791208. Width is 1.3 mm. Unpolarized light.

a. Fragment of cumulate eucrite-like clast (MC8) with partly inverted pigeonite host and (001) augite lamellae.

b. Gabbroic clast (GB8).

c. Aphanitic clast with plagioclase fragments.

d. Aphanitic clast (AP) with dark glassy matrix and fragments of Mg-rich orthopyroxene.

Table 5. Selected pyroxene compositions (wt %) of mineral fragments and lithic clasts in Y-791208.

Remarks	Frag. 1 Opx clast	MC-clast Opx host	MC-clast Pig bulk	MC-clast Aug lamella	Frag. Pig cum-Euc	GB-clast Pig host	GB-clast Pig bulk	GB-clast Aug lamella	Frag. Pig o-Euc
SiO_2	53.36	51.75	49.71	51.66	49.94	49.86	50.89	50.03	48.46
Al_2O_3	1.06	0.35	0.53	0.63	0.50	0.19	0.28	0.60	0.18
TiO_2	0.12	0.22	0.32	0.43	0.28	0.19	0.37	0.35	0.46
Cr_2O_3	0.66	0.15	0.55	0.27	0.43	0.11	0.31	0.25	0.67
MgO	27.33	19.08	17.02	13.84	16.12	14.78	13.41	12.23	12.39
FeO	15.09	26.34	21.92	9.97	29.18	31.76	28.53	14.57	35.58
MnO	0.52	0.85	0.81	0.52	0.89	0.90	0.81	0.44	1.18
CaO	1.25	0.89	5.51	21.65	0.98	1.62	5.64	20.56	1.76
Na_2O	0.03	0.00	0.04	0.11	0.02	0.02	0.03	0.10	0.00
Total	99.43	99.64	96.41	99.08	98.33	99.42	100.28	99.13	100.68
Si*	1.943	1.980	1.948	1.960	1.972	1.974	1.985	1.939	1.940
Al	0.046	0.016	0.025	0.028	0.023	0.009	0.013	0.027	0.008
Ti	0.003	0.006	0.009	0.012	0.008	0.006	0.011	0.010	0.014
Cr	0.019	0.004	0.017	0.008	0.013	0.003	0.010	0.008	0.021
Mg	1.484	1.089	0.995	0.783	0.949	0.872	0.780	0.706	0.740
Fe	0.460	0.843	0.719	0.316	0.963	1.051	0.931	0.472	1.192
Mn	0.016	0.028	0.027	0.017	0.030	0.030	0.027	0.015	0.040
Ca	0.049	0.037	0.280	0.880	0.042	0.069	0.236	0.854	0.076
Na	0.002	0.000	0.003	0.008	0.001	0.001	0.003	0.007	0.000
Total	4.022	4.003	4.023	4.013	4.001	4.013	3.996	4.038	4.031
Ca**	2.5	1.9	14.0	44.5	2.1	3.5	12.1	42.0	3.8
Mg	74.5	55.3	49.9	39.6	48.6	43.8	40.1	34.8	36.9
Fe	23.1	42.8	36.1	16.0	49.3	52.8	47.8	23.2	59.4

*Cations per six oxygens.
**Atomic per cent.

Juvinas. The modal abundance of minerals are: plagioclase 70 and pyroxene 30 per cent.

Some portions of the matrix are dark fine-grained and appear to be shock darkened aphanitic clasts. One such a clast has a few fragments of plagioclase set in a cryptocrystalline dark matrix (Fig. 5c). Another dark impact melt clast (AP) has inclusions of fine-grained irregular fragments of Mg-rich pyroxene set in a dark glassy matrix (Fig. 5d).

Microprobe analyses show a wide range in pyroxene composition similar to that of Y-790727 (Fig. 2). The most abundant compositions of pyroxene fragments are around those of diogenite, but the compositions extend toward the Mg-rich side. The compositions of the most Mg-rich pyroxene ($Ca_{0.7}Mg_{84.1}Fe_{15.1}$) are those in the fine phenocrysts in a glassy matrix of AP, but those of the large fragments (Frag. 1 in Table 5) also approach this composition. The most Fe-rich pyroxene extends beyond the common eucritic compositions. Cumulate eucrite-like pyroxenes are not rare. Olivine compositions (Table 3) range from Fa_{10} to Fa_{33}.

Plagioclase composition ranges from An_{93} to An_{80} (Table 4). The plagioclase fragments in an aphanitic clast have more An-poor composition (An_{92} to An_{80}, Table

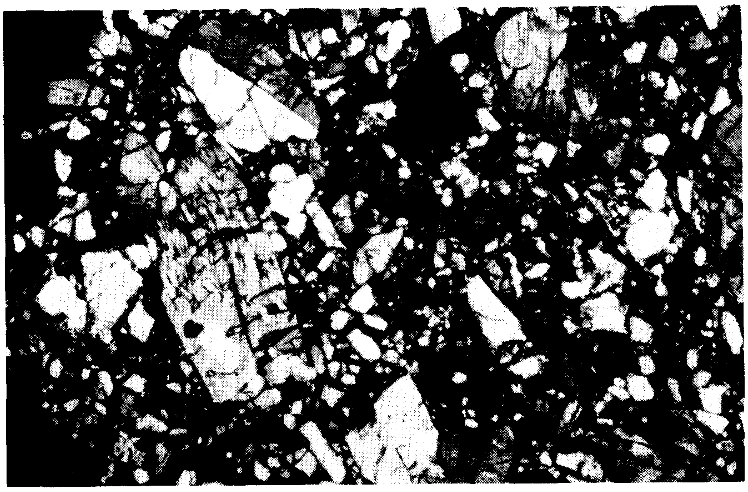
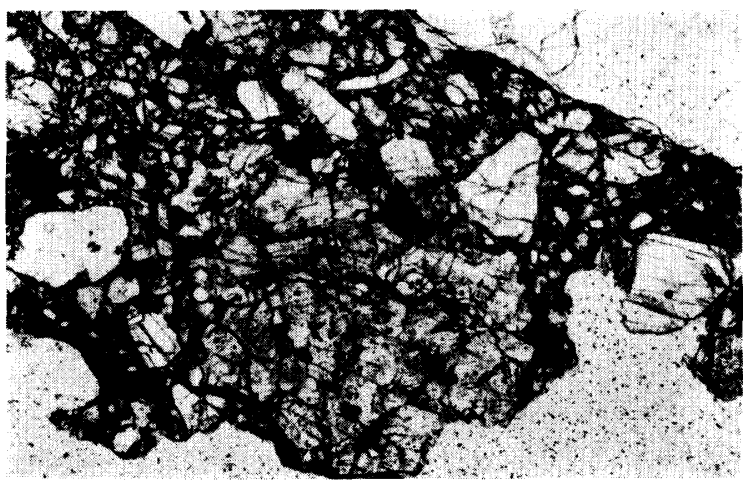


Fig. 6. Photomicrographs of mineral and lithic clasts in Y-791492. Width 1.3 mm.

a. An inverted pigeonite (BD1) from a Binda-like cumulate eucrite. Polarized light.



b. Augite-rich clast (AG2) with silica and Fe-rich opaques. Unpolarized light.

4 and Fig. 3). The plagioclase of the GB8 clast is slightly zoned from An_{92} to An_{89}, and that of the MC8 clast nearly uniform $An_{91.5}$ (Fig. 3).

3.6. Y-791492

This is a 41.1 g stone and 4.2×2.9×2.7 cm in size. More than a half of a conical stone is covered with black fusion crust, except for one broken surface and an eroded bottom face. The broken surface is light brownish gray, and white plagioclase and yellow to brownish pyroxene fragments are set in fine dusty matrix with comminuted mineral and lithic fragments.

A thin section shows complex breccia of angular fragments up to 2 mm long, of orthopyroxene, inverted pigeonite, pigeonite, olivine, plagioclase, chromite, ilmenite, silica and other opaques, set in a matrix of comminuted mineral fragments. Lithic clasts are rather rare in comparison with other two Yamato-79 howardites. The matrix does not show rusty staining as was observed in Y-791208.

Many orthopyroxene fragments do not show the exsolution of augite that was observed in diogenites (MORI and TAKEDA, 1981a), but they may be similar to diogenites. One orthopyroxene fragment 1.1×0.47 mm in size has a small chromite attached to the edge (DC). Two subround fragments of cumulate eucrite pyroxene include oriented blebby inclusions of augite (Fig. 6a). One grain (BD1) is 0.32×0.54 mm in size. Fe-rich eucritic pigeonite shows exsolution of augite on (001). Three small eucritic lithic clasts (EC8, 9, 29) were observed, in which pigeonite also shows exsolution. However, pigeonites in a plagioclase-rich eucritic clast do not show exsolution. The plagioclase compositions in EC8, 9, 29 differ from one clast to the other (Fig. 3). One small augite-rich clast (AG2) 0.72×0.53 mm in size (Fig. 6b) includes a silica mineral and opaque iron minerals.

Microprobe analyses show a wide range in pyroxene composition as was observed in other two howardites (Fig. 2). The compositions of the diogenitic pyroxenes are almost the same as in Y-791208. The most Mg-rich diogenitic pyroxene fragment is low in Ca content ($Ca_1Mg_{83}Fe_{16}$, Frag. Opx in Table 6). Two BD pyroxene clasts have chemical compositions similar to Moama (Table 6). Pyroxene fragments of this type are common. The tie-lines of the host-lamella compositions of the exsolved eucritic pigeonites are the same as those of the ordinary eucrites. Pyroxenes more Fe-rich than this composition are rare. The augite composition in the augite-rich clast (AG2) is uniform ($Ca_{43}Mg_{28}Fe_{29}$). Plagioclase fragments ranges in composition and is zoned from An_{81} to An_{91} (Table 4 and Fig. 3). A large chromite fragment rich in Mg is similar to that of the diogenite-like clast (DC), but one rich in Ti may be that of eucrites (Table 3).

3.7. Transitional achondrites to diogenite and cumulate eucrite

Two specimens in Yamato-79 collection (Y-791200 and -791201) are texturally similar to the Y-75032-type achondrite, but include some true cumulate-eucrite components in addition to diogenitic ones. Very dark glassy matrices fill interstices of subangular fragments of shocked pyroxenes. Devitrified maskelynite fragments up to 1.2×0.65 mm in size in Y-791200 are present. Minor chromite and troilite are present in both clasts and matrix.

Y-791200 is nearly complete oblong stone (51.58 g, 4.3×3.1×2.5 cm in size) with

Table 6. Selected pyroxene compositions (wt %) of mineral fragments (Frag.) and lithic clasts in Y-791492.

Remarks	Frag. Opx Mg-rich	Frag. DC Opx chromite	BD1-clast Opx host	BD1-clast Pig bulk	BD1-clast Aug blebs	Frag. Euc Pig host	Frag. Euc Aug lamella	Aug-clast Aug grain
SiO_2	56.22	54.31	51.62	51.60	51.91	49.62	49.81	51.87
Al_2O_3	0.30	0.89	0.47	0.51	0.90	0.42	0.75	0.42
TiO_2	0.05	0.08	0.32	0.39	0.50	0.17	0.48	0.18
Cr_2O_3	0.75	0.41	0.15	0.23	0.30	0.20	0.28	0.24
MgO	31.50	27.21	19.63	18.10	13.90	13.92	10.20	9.75
FeO	10.62	15.22	24.78	23.83	10.22	32.69	17.27	16.19
MnO	0.33	0.46	0.89	0.74	0.37	0.95	0.59	0.56
CaO	0.43	0.68	1.17	3.74	21.66	1.40	19.04	20.94
Na_2O	0.00	0.03	0.02	0.03	0.09	0.00	0.10	0.11
Total	100.20	99.29	99.07	99.14	99.85	99.38	98.54	100.25
Si*	1.978	1.972	1.976	1.977	1.954	1.973	1.958	1.994
Al	0.013	0.038	0.021	0.023	0.040	0.020	0.035	0.019
Ti	0.001	0.002	0.009	0.001	0.014	0.005	0.014	0.005
Cr	0.021	0.012	0.004	0.007	0.009	0.006	0.009	0.007
Mg	1.652	1.473	1.120	1.036	0.780	0.825	0.598	0.559
Fe	0.312	0.462	0.793	0.765	0.322	1.087	0.568	0.520
Mn	0.010	0.014	0.029	0.024	0.012	0.032	0.020	0.018
Ca	0.016	0.027	0.048	0.154	0.874	0.059	0.802	0.862
Na	0.000	0.002	0.002	0.002	0.006	0.000	0.008	0.008
Total	4.004	4.002	4.003	3.988	4.011	4.009	4.010	3.992
Ca**	0.8	1.4	2.4	7.8	44.2	3.0	40.8	44.4
Mg	83.4	75.1	57.1	53.0	39.5	41.9	30.4	28.8
Fe	15.8	23.6	40.4	39.1	16.3	55.1	28.9	26.8

*Cations per six oxygens.
**Atomic per cent.

a few shiny black fusion crust, and contain dark yellow pyroxene fragments up to 3 mm in diameter, set in a dark glassy matrix. There is a brecciated matrix containing plagioclase. A triangular clast 2×1.5 cm in size contains olive yellow pyroxene. A coarse-grained noritic clast 1.0 cm in diameter composed of dark olive pyroxene and a few plagioclase is exposed on a surface in hand specimen (KOJIMA and YANAI, 1981), but is not included in the thin section examined. A pyroxene crystal about 1 mm in diameter separated from the clast has been confirmed to be orthopyroxene, but its bulk chemical composition $Ca_6Mg_{57}Fe_{37}$ is more Ca-rich and Fe-rich than most of the pyroxenes in Y-75032 and -791422 (TAKEDA and MORI, 1984). The oriented thin section of the single crystal shows exsolution lamellae about 1 μm thick with (100) in common with the host orthopyroxene. This pyroxene may be a low-Ca inverted pigeonite.

One pyroxenite clast 1.6×1.4 mm in size in Y-791200 consists of a few grains of orthopyroxenes with irregularly thickened and thinned lamella-like inclusions of augite on (100). The pyroxene is different from those in diogenites (MORI and TAKEDA, 1981a) and may be a low-Ca inverted pigeonite. The exsolution and inversion texture of this type is not known previously (ISHII and TAKEDA, 1974). Another clast 1.2×1.3 mm in size consists almost entirely of a shocked low-Ca pyroxenes, minute plagioclase and a small primary augite grain 0.75×0.34 mm in size, with fine exsolution lamellae. Such primary augite has been reported in Y-75032 (TAKEDA *et al.*, 1979). Some clasts have a close affinity to diogenites.

Y-791201 is a nearly complete subrounded stone (9.6 g, 2.4×1.8×1.7 cm in size) and contains one broken surface, where a nearly crystalline texture can be seen. Smooth thin shiny black fusion crust with many bubbles, covers 75 per cent of the meteorite. A coarse-grained eucritic clast with 1–3 mm light brown pyroxene and white plagiocalase is present, but a few portions are poor in plagioclase and resemble Y-75032.

One large noritic clast 4.1×1.5 mm in size texturally similar to that in Y-791200 and to the Moama cumulate eucrite is attached on one side of the thin section of Y-791201. It consists of 36% orthopyroxene, 61% plagioclase (An_{89}) and 3% blebby augite. The pyroxenes with round shape about 1 mm in diameter and with blebby inclusions of augite aligned along one crystallographic direction may be a low-Ca inverted pigeonite. The bulk pyroxene composition $Ca_7Mg_{58}Fe_{35}$ is intermediate in the Mg/(Mg+Fe) ratio among the pyroxene fragments in the matrix. The Mg/(Mg+Fe) ratios of many other lithic clasts with approximately half pyroxene and half plagioclase are slightly above 0.5. They are definitely cumulate eucrites.

Modal abundance of plagioclase in Y-791200 is 9 per cent, but 10 was reported for another thin section by DELANEY *et al.* (1984). Y-791200 has some features of cumulate eucrite. Y-791201 includes large amounts of cumulate eucrite component than Y-791200. Modal abundance of plagioclase in Y-791201 is 25 per cent. The Mg/(Mg+Fe) atomic ratios of pyroxene range from 0.7 to 0.5 and cover an entire range between Fe-rich diogenites and cumulate eucrites. The An contents of plagioclase range from 86 to 93. Although these polymict or genomict cumulate eucrites contain diogenitic components, no basaltic component and olivine, which are characteristic of howardites are found, and their shocked textures are entirely different from those of ordinary howardites. The other Y-75032-type achondrites have more close affinity to diogenite than the above two achondrites.

4. Discussion

The bulk chemical compositions of three Yamato-79 howardites (Table 1) analyzed by H. HARAMURA (Geol. Inst., Univ. of Tokyo) are similar and plot in the middle of the diogenite-eucrite trend in the Al_2O_3 *vs.* CaO diagram (Fig. 1), close to that of Binda, the most Mg-rich eucrite. These howardites are different in composition from Y-7308, which is the most diogenite-rich howardite (TAKEDA *et al.*, 1976).

Although these howardites were found in a region not far from the area where the Yamato polymict eucrites were found in the Yamato meteorite field (YANAI, 1979), they are distinct from the Yamato polymict eucrites and Y-7308 howardite. They are very similar to a common group in the non-Antarctic collection (MASON *et al.*, 1979). We cannot definitely state that three howardites are pieces from a single fall, because the degree of rusty staining in the matrices and clast-types are different in spite of the similarity in the bulk composition, but there is a possibility. Counting these howardites as one piece, we have four distinct eucrites and two howardites in the Yamato collection. The statistics are not much different from the other collections.

Mineral components in these howardites are similar to those of Antarctic and non-Antarctic howardites already described (DYMEK *et al.*, 1976; LABOTKA and PAPIKE, 1980; NEHRU *et al.*, 1981; PRINZ *et al.*, 1980; TAKEDA *et al.*, 1976). It is to be noted that although dominant composition of the orthopyroxene clusters around those of known diogenitic orthopyroxenes (FREDRIKSSON *et al.*, 1976), they extend towards the more Mg-rich side up to Mg/(Mg+Fe)=0.85 (atomic per cent) without any gap, and that although dominant compositions of eucritic pigeonite cluster around the known ordinary eucrites (MASON *et al.*, 1979), there are many pyroxenes between diogenites and the ordinary eucrites. The Ca contents of the orthopyroxenes more Mg-rich than those in diogenites gradually decrease towards the most Mg-rich end. The most Mg-rich orthopyroxene composition may approach $Ca_{0.5}Mg_{85}Fe_{14.5}$.

In spite of the similarity in mineral components between the three Y-79 howardites, we found six distinct lithic and mineral clasts in these howardites. They are MC8, GB8, BD1, GD7, RD7 and AG2 clasts. The chemical compositions of the pigeonite in the MC8 clast are similar to those in the Medanitos cumulate eucrite (DELANEY *et al.*, 1983a).

Such clasts have been rarely described among the howardites (BUNCH, 1975). The bulk composition of the GB8 pigeonites in Y-791208 is more Mg-rich than those in many ordinary eucrites (Table 5). This clast may be in the extreme end of the eucrite field but fills the gap between the cumulate eucrites and ordinary eucrites in the non-Antarctic collection. The AG2 clast may not be simply explained by the existing models, because the augite-rich basalt is unlikely to be partial melts from the same source materials as that of the eucrites (NEHRU *et al.*, 1983). Such a clast may be produced by extensive fractionation of partial melts.

The presence of many other pyroxene fragments intermediate between the diogenites and ordinary eucrites, in addition to the above clasts, is in line with the findings in Y-7308 (TAKEDA *et al.*, 1976; MIYAMOTO *et al.*, 1978; NEHRU *et al.*, 1983; IKEDA and TAKEDA, 1984), and gives strong support for the crystal fractionation from a primary magma of IKEDA and TAKEDA (1984) and DELANEY *et al.* (1981), or from a magma produced by partial melting, as the origin of the crust of the howardite parent body. From a magma of the ordinary eucrite composition with Fe/(Fe+Mg)=0.6 (atomic ratio) produced by partial melting, pyroxenes with wide compositional ranges between Fe/(Fe+Mg)=0.31–0.9 will be produced by fractional crystallization (POWELL *et al.*, 1980). However, diogenitic pyroxenes more magnesian than ordinary diogenites cannot be generated. NEHRU *et al.* (1983) also mentioned that the partial melting model for the eucrites may not be extended to these magnesian compositions.

The presence of GB8-clast-like eucrites in general between Moore County (MORI and TAKEDA, 1981b) and the ordinary eucrites can be interpreted by the existing models as follows: (1) They are crystallization products from a more fractionated magma than Moore County for the fractional crystallization model (MCCARTHY *et al.*, 1973); (2) they are solidified liquids of less fractionated residual magma than the ordinary eucrites of a model by IKEDA and TAKEDA (1984); or (3) they were crystallized from a melt produced by more advanced degree of partial melting than Sioux County for a partial melting model (CONSOLMAGNO and DRAKE, 1977; STOLPER, 1977).

If we introduce a model, in which crystal accumulation is involved, GB-like eucrites can be produced by slight accumulation of plagioclase and pyroxene crystals and loss of small amounts of fractionated residual liquid from a primary eucritic magma of STOLPER (1977) and TAKEDA *et al.* (1978). The gabbroic texture and absence of mesostasis rich portion common in ordinary eucrites and of chemical zoning both in pyroxene and plagioclase are in agreement with the model, assuming that lack of zoning is not a later event. The lack of zoning in the ordinary eucritic pigeonite is due to homogenization by a later high temperature event, unrelated to magmatic history, but their plagioclase preserves zoning and the texture is quickly cooled basaltic. However, REE abundance data and bulk chemical compositions should be available for such large clasts, before we draw any definite conclusions on this subject.

Because the existing models for the origin of eucrites and diogenites are not completely satisfactory to account for the continuum of their chemical compositions of mineral and lithic clasts in howardites, we review the new model of crystal fractionation, and propose an alternate model on the basis of our present observation.

The sequence of fractional crystallization of the HED magma has been explained in terms of compositions of fractionated liquids (See figures of IKEDA and TAKEDA, 1984). The primary magma was assumed to have been produced by melting of an LL chondrite-like material and by volatile loss. Oxygen isotopes have to be homogenized at high temperature stage.

The sequence of chemical aspect of fractional crystallization of the HED magma is summarized as below according to their first model. The primary magma (liquid A) changes to magnesian eucritic magma (liquid B) by subtraction of olivines, forming "cumulate dunites". If magmas around B solidify as volcanic rocks on the surface of the parent body, they may become noncumulate pigeonite-eucrites such as No. 1 pigeonite-eucrite clast in Y-7308 of IKEDA and TAKEDA (1984).

When the magma changes from B to more iron-rich magma (liquid D), cumulate diogenites are formed by the crystallizaion of diogenitic orthopyroxenes. When the magma changes from D to the most iron-rich one (liquid E to F), cumulate hypersthene-eucrites and cumulate inverted-pigeonite eucrites are formed. If the magmas D to F solidify as volcanic rocks, they become noncumulate pigeonite-eucrites. The final solidified magma produces noncumulate fayalite-hedenbergite-tridymite-plagioclase rocks. After consolidation of these rocks, they were recrystallized under subsolidus conditions and then comminuted and completely mixed with each other, resulting in breccias known as howardites, polymict eucrites or polymict diogenites depending on the relative abundance of clast types.

Detailed physical processes to produce each components of the layered crust of the howardite parent body, are given by IKEDA and TAKEDA (1984). They are summarized as below: The magma pool was called a shallow magma ocean, because large areas of the surface of the howardite parent body were assumed to be surrounded by magma. The depth of the ocean may be comparable to that of terrestrial layered intrusions. The shallow magma ocean corresponding to liquid A in chemical composition cooled slowly by the heat loss from the surface. At the bottom floor of the magma ocean, "cumulate dunites" may form by the settling of olivines crystallizing in the magma. A crust formed on the surface may correspond to ordinary eucrites. Then, by the crystal fractionation, diogenite and cumulate eucrite may be formed by the processes explained above.

The clustering in composition around the peritectic point in silica-olivine-plagioclase pseudo-ternary system can be explained by the partial melting model easier than the fractional crystallization (STOLPER, 1977). However, the compositional continuity of the mineral compositions in many howardites is difficult to explain by the partial melting model. Some alternate models can be proposed if we accept a succesive two stage model. In these models, the internal heat source has to be dominant, because after the first partial melting, the residual has to be heated to initiate an advanced partial melting, for two stage heating models. For an accretional heating model (TAKEDA *et al.*, 1979), we do not have this kind of problem.

The first model of the two stage heating has been examined by IKEDA and TAKEDA (1984). This model involves partial melting of cumulate eucrites produced by the first stage crystal fractionation, which are represented by a Na-rich trend in An *vs.* En diagram (IKEDA and TAKEDA, 1984). For the second stage crystal fractionation, the liquid produced by partial melting is on the peritectic point, and therefore there may be no problem as to their crystallization history.

The second model invokes some new processes. At the first stage, a eucritic magma produced by partial melting in the interior of the parent body may erupt on the surface to produce ordinary eucrite lavas. Because pyroxenes known in Y-75032-type achondrites, which link Fe-rich diogenite and cumulate eucrite can be crystallized from an ordinary eucrite magma, the fractional crystallization proposed by IKEDA and TAKEDA (1984) may take place on an area where the extruded or intruded lava is thick. The cumulate eucrites such as Binda, Moama, Serra de Magé and Moore County may be produced by this process.

At the second stage, by successive rise of temperature in the interior of the parent body, the residues produced by the first stage partial melting, which still includes plagioclase, and a primitive materials left beneath the residues, may again partially melted and produce a magma, from which ordinary diogenites crystallize at the bottom of the previously erupted lava. Because of the high melting point of the Mg-rich magma, they may crystallize quickly producing diogenites with narrow compositional range without extensive fractional crystallization. This trend may correspond to that of the diogenitic magma of HEWINS (1983).

The third model has been proposed by TAKEDA *et al.* (1979), to demonstrate that the fractionated liquid composition stays at the peritectic point even for the crystal fractionation model. The early model requires some revisions, and detailed modeling is required before comparing it with other model. When the HED parent body grows, it begins to melt by accretional heating when the size of the planetessimal reached a certain limit. If the luminosity of the sun is high, the size can be smaller. The initial melting is moderate and the degree of partial melting is small. Then, during the extensive growth period, advanced partial melting may take place, and the liquid composition moves away from the peritectic point toward the pyroxene side along the pyroxene-olivine cotectic line. The liquid composition never leaves this line by supply of accreting primitive materials, while crystallizing diogenitic pyroxene at a cooler base of the melted zone. The residue of partial melting including olivine may be incorporated into the settling pyroxene crystal and finally be well homogenized. The howardite olivine can be produced by this process.

At the last stage of the accretion, the amount of accreting materials decreases and the liquid composition moves to the peritectic point by crystal fractionation similar to what has been introduced by IKEDA and TAKEDA (1984). However, the liquid composition stays on the peritectic point, while the supply of the primitive materials still continue. As soon as the accretion stops, temperature of the surface decreases rapidly, and the eucritic liquid solidifies to produce ordinary basaltic eucrites. By accumulation of heat in the interior, partial melting of the residue at the hot base of the eucritic layer, may still continue and a lava like eucrite may be formed by eruption from the interior.

The presence of howardites with various amounts of diogenite, cumulate eucrites, and ordinary eucrites, and of polymict eucrites with various amounts of cumulate eucrites and lava-like eucrites (Pasamonte–Yamato-75011-type), gives strong support on the presence of a layered crust of the HED achondrites (TAKEDA, 1979). The Yamato-79 howardites sample all components somewhat equally, and Y-7308 samples diogenite-rich suites. This suggests that the meteorite impact that produced the Y-79 howardite breccias, might have been smaller scale than that of Y-7308.

If crystal fractionation and a shallow magma ocean hypothesis were accepted, the crust would be the most primitive planetary type crust formed in the solar system. The mechanism of formation will provide us useful information to understand the crust formation of Earth, the Moon and other planets.

Summary, (1) Yamato-79 howardites are chemically and mineralogically intermediate between ordinary endmember diogenites and eucrites, and are distinct from Y-7308, the only known Antarctic howardite, (2) Large lithic clasts observed in these howardites include, a cumulate eucrite with a partly inverted pigeonite, a gabbroic eucrite intermediate between the Moore County cumulate eucrite and ordinary eucrites, and an augite rich clast with a silica mineral, and (3) the origin of these lithologies appears to be difficult to explain by a simple partial melting model or a crystal fractionation model, and to require two stage models involving a crystal fractionation from a partial melt or second partial melting of the residues of the partial melt, or of the cumulate eucrites, or crystal fractionation from a liquid whose composition is buffered by the accreting primitive materials.

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