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MODAL MINERAL ABUNDANCES AND THE DIFFERENTIATION TRENDS IN PRIMITIVE ACHONDRITES

Keiko YUGAMI[1]*, Hiroshi TAKEDA[2], Hideyasu KOJIMA[3] and Masamichi MIYAMOTO[1]

[1]*Mineralogical Institute, Graduate School of Science, University of Tokyo,*
Hongo, Bunkyo-ku, Tokyo 113-0033
[2]*Research Institute, Chiba Institute of Technology, Tsudanuma, Narashino 275-0016*
[3]*National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*

Abstract: The mineral distribution maps of polished thin sections (PTSs) of acapulcoites (Acapulco, Allan Hills (ALH) 77081, ALH78230, Elephant Moraine (EET) 84302 and Yamato (Y)-8307) and lodranites (Gibson, MacAlpine Hills (MAC) 88177, Y-74357, Y-75274, Y-791491 and Y-8002), winonaites (Tierra Blanca, Y-74025, Y-75305 and Y-8005), silicate inclusions in IAB iron meteorites (Y-791058 and Caddo County), and an H7 chondrite (Y-75008) were made from elemental distribution maps of the electron probe microanalyzer to obtain quantitative modal abundances of minerals, and to study variations in the distributions of minerals. The trends of variations of chemical compositions of minerals were also studied. Other related meteorites, ALH81187 and ALH81261 (acapulcoites) were also studied for comparison.

Textures of these meteorites are various from fine-grained recrystallized chondrite-like materials including minerals known in chondrites, to coarse-grained materials with opaque mineral grains which have complex shapes, often with large aggregates of Fe-Ni metal. The variety of modal abundances and textures of primitive achondrites suggests that heterogeneity produced by local segregation of partially melted materials on their parent bodies can explain the origin of variation of primitive achondrites. Systematic variations in the relative abundances of olivine, augite+plagioclase, and orthopyroxene shows that the plagioclase-augite-rich region of Caddo County B3A (augite+plagioclase=96.8%) can be taken as an endmember of the variations observed in other primitive achondrites. The orthopyroxene-chromite-rich region of EET84302,19 (orthopyroxene=95.1%) and Y-74357 (olivine=83.2%) are other types of segregated materials.

The mechanism proposed in this paper reveals the early differentiation processes of planetesimals from primitive source materials.

1. Introduction

Winonaites and IAB iron meteorites (WI) and acapulcoites and lodranites (AL) are both sub-groups of primitive achondrites, although their oxygen isotope compositions indicate that they are from different parent bodies (*e.g.*, CLAYTON and MAYEDA, 1996). Recently, comprehensive studies have been conducted of these meteorite groups and more detailed imformation and models for their formation have been published; *e.g.*, KIMURA *et al.* (1992), NAGAHARA (1992), TAKEDA *et al.* (1994), BENEDIX *et al.* (1996),

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[*] Present address: X-ray Research Laboratory, Rigaku Corporation, Matsubara-cho, Akishima-shi, Tokyo 196-8666.

Mittelfehldt *et al.* (1996), and McCoy *et al.* (1997a,b).

The distinction of winonaites and IAB irons, and that of acapulcoite and lodranites are somewhat different among the previous investigators (*e.g.*, Prinz *et al.*, 1980; Kimura *et al.*, 1992; McCoy *et al.*, 1993). Here we tentatively call Metal-rich members of WI (Caddo County and Y-791058) as IAB irons, and other members of WI (Winona, Tierra Blanca, Y-74025, Y-75305 and Y-8005) as winonaite. We tentatively call the members which are coarser-grained than Acapulco (Gibson, EET84302, Y-74357, Y-75274, Y-791491, Y-8002, and MAC88177) as lodranite, and other members of AL (Acapulco, ALH77081,4, ALH78230,51-2, ALH81187,16, ALH81261,14, Y-8307) as acapulcoite according to the definition of McCoy *et al.* (1993).

Some areas rich in plagioclase and augite within the PTSs were found in EET84302 and Caddo County (Takeda *et al.*, 1994) and much larger, more enriched areas in cm scale were found in the Caddo County IAB iron meteorites (Takeda *et al.* 1997). McCoy *et al.* (1997b) also detected similar area in LEW86220. However, their interpretations are not totally in agreements as we discuss later.

The mineral distribution maps of polished thin sections (PTSs) of five winonaites, two silicate inclusions in IAB iron meteorites, and winonaite-related sub-groups of primitive achondrites, four acapulcoites, six lodranites and an H7 chondrite (Y-75008) were made from elemental distribution maps of the electron probe microanalyzer to obtain quantitative modal abundances of minerals, and to study variations in the distributions of minerals. The trends of variations of chemical compositions of minerals were also studied from these data, in order to look for a common formation process from primitive source materials.

2. Samples and Techniques

The polished thin sections (PTSs) of five winonaites, Tierra Blanca, Winona, Y-74025,52-4, Y-75305,52-2, and Y-8005,51-3, and three PTSs of Caddo County IAB iron meteorite, Caddo County,B1A,B2A,B3A and two PTSs of Y-791058 (WI group), Y-791058,51-2 and 91-2 and twelve meteorites in the AL group, Acapulco, ALH77081,4, ALH78230,51-2, ALH81187,16, ALH81261,14, EET84302,28, Y-74357,62-1, Y-75274,81-2, Y-791491,61-2, Y-8002,51-2, Y-8307,51-2 and MAC88177,17 were studied. The Y-75008 H7 chondrite was also studied as a hypothetical standard source material for primitive achondrites for comparison. These samples were supplied from National Institute of Polar Research, Meteorite Working Group of the U.S. and Planetary Materials Database Collections of the University of Tokyo. The PTSs of Caddo County were made by the courtesy of Dr. Don Bogard as part of cooperative research with one of the authors (H. Takeda).

These PTSs were investigated by EPMA JEOL JXA-733 at Ocean Research Institute and Geological Institute and JEOL JXA-8900L at Geological Institute, University of Tokyo. Two dimensional CMA techniques of EPMA for nine elements (Si, Mg, Ca, Fe, Al, Cr, P, S, Ni) have been applied to twenty-one PTSs and mineral distribution maps of eighteen primitive achondrites and a chondrite Y-75008 were made from CMA data processed by using the public domain program NIH Image version 1.57. Distribution maps of eleven minerals (olivine, orthopyroxene, augite, plagioclase, Fe-Ni metal, troilite, chromite, Ca-phosphate, schreibersite, and daubreelite, and weathering products (Fe-hydroxides)), of each PTSs were made and combined (YUGAMI, 1996). Modal abundances of minerals of these samples were obtained by counting number of pixels for each minerals in the mineral distribution maps. The errors of modal abundances of minerals were estimated by repeating the same operation to determine which pixel should belong to which mineral and counting the difference of the modes. The error depends on the grain sizes. The errors of finer-grained PTSs tend to be larger. The estimated errors range about 0.7% (Caddo County) to 9% (Y-8005).

3. Results

3.1. *Descriptions of thin sections*

Y-8005

The silicate minerals of Y-8005 (Fig. 1a) are very fine-grained (0.02–0.2 mm). The modal abundance of minerals of Y-8005 obtained from the mineral distribution map (Fig. 2a) are shown in Table 1. Orthopyroxene (Opx) and olivine (Ol) are reverse-zoned, showing an increase in Mg/Fe towards the rims. The average *fe#* (= Fe/(Fe+Mg) atomic ratio) of cores of Ol grains is 2.1 and that of Opx ($En_{96.6}Fs_{2.0}Wo_{1.5}$) is 1.9. The Ca content of plagioclase (Plag) of Y-8005 ($An_{11.2}$) is lower than other winonaites (Table 2d) (KIMURA *et al.*, 1992). PTS Y-8005,51-3 is characterized by presence of a very large kamacite grain (5.7 mm^2, 8 vol% of the PTS, Ni 6.36 wt%) (YUGAMI *et al.*, 1996a) including schreibersite (Ni 41.4 wt%) and taenite grains (Fig. 2a). Y-8005 rarely includes medium-sized opaque grains. The large opaque grains in Y-75305 and Y-8005 are mainly Fe-Ni metal and most troilite grains exist as smaller grains among silicate minerals. Cr in troilite is 0.37 wt% and it is similar to the values of other winonaites. The large metal grains (except for the extremely large one) have complicated shapes that resemble the opaque grains in EET84302 (Fig. 1b).

Y-8307

This meteorite has been described as a primitive achondrite (YANAI and KOJIMA, 1995), but it has not been determined to which sub-group it belongs. It is similar to typical acapulcoites such as ALH77081 and ALH78230 in texture (Fig. 1c), and is slightly coarser grained (about 0.3 mm in diameter) than them. The largest Ol grain is about 0.8 mm across. Some fault-like lines can be seen in the PTS (YUGAMI *et al.*, 1996b). Its pyroxene grains do not have dusty cores like those of Acapulco (Fig. 1d) and EET84302. The modal abundances of minerals of Y-8307 obtained from the mineral distribution map (Fig. 2b) in this study are shown in Table 1. Opx grains with small amounts of dusty inclusions in Y-8307 show CaO zoning similar to Opx grains with dusty cores in Acapulco and EET84302. The augite (Aug) is distributes heterogeneously and is concentrated in some zones, whereas the distribution of Plag ($An_{15.0}$) is homogeneous. No Fe/Mg zoning of pyroxene or Ol was detected. The average *fe#* of Ol is 10.7 and that of Opx ($En_{88.4}Fs_{9.9}Wo_{1.6}$) is 10.1.

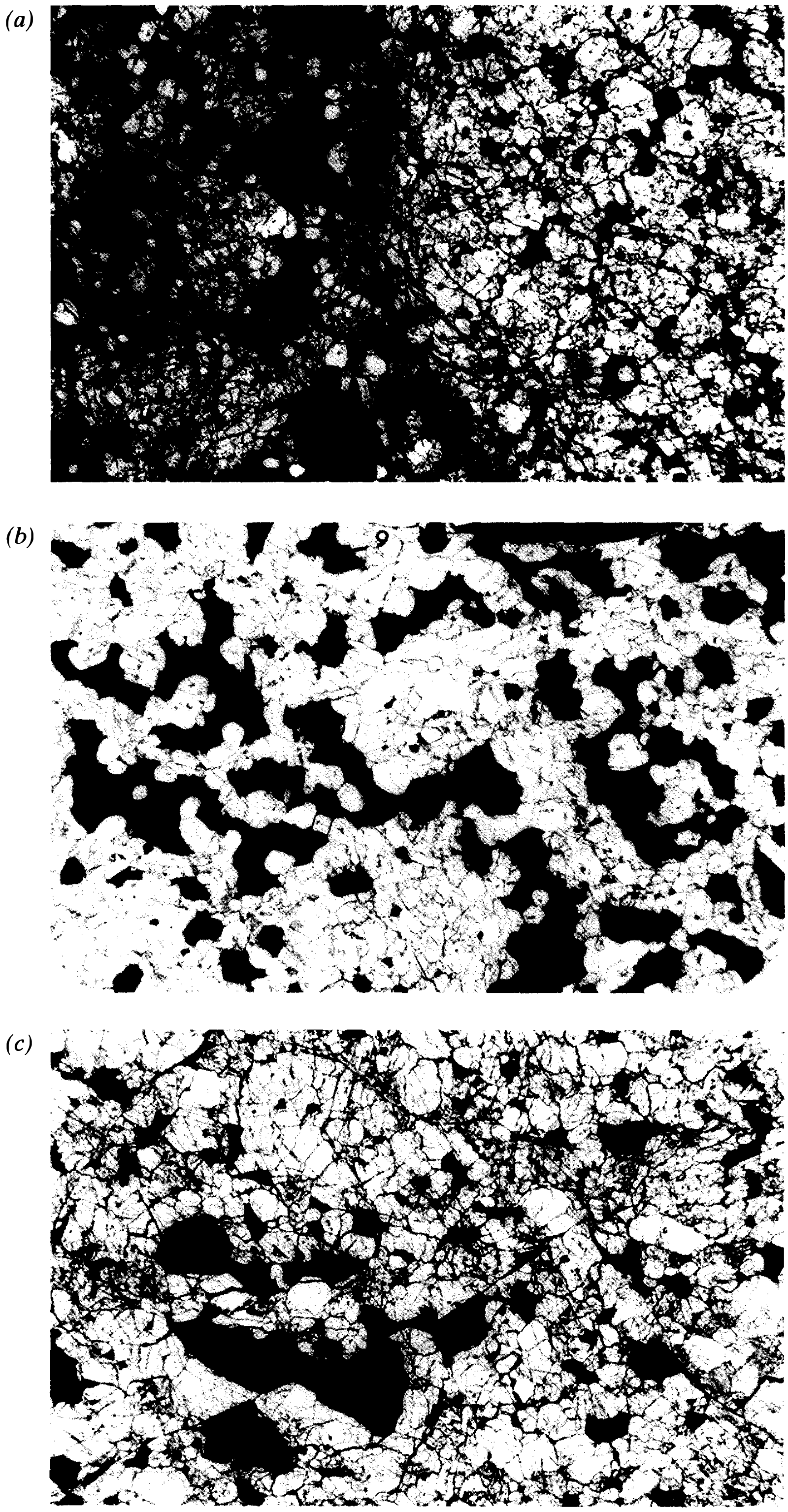

Fig. 1. Photomicrographs of primitive achondrites. Transmitted light.
a. Y-8005 (winonaite), width=2.5 mm.
b. EET84302,28 (a meteorite with lodranite-like grain size and acapulcoite-like modal mineral abundances), width=8 mm.
c. Y-8307 (acapulcoite), width=2.5 mm.

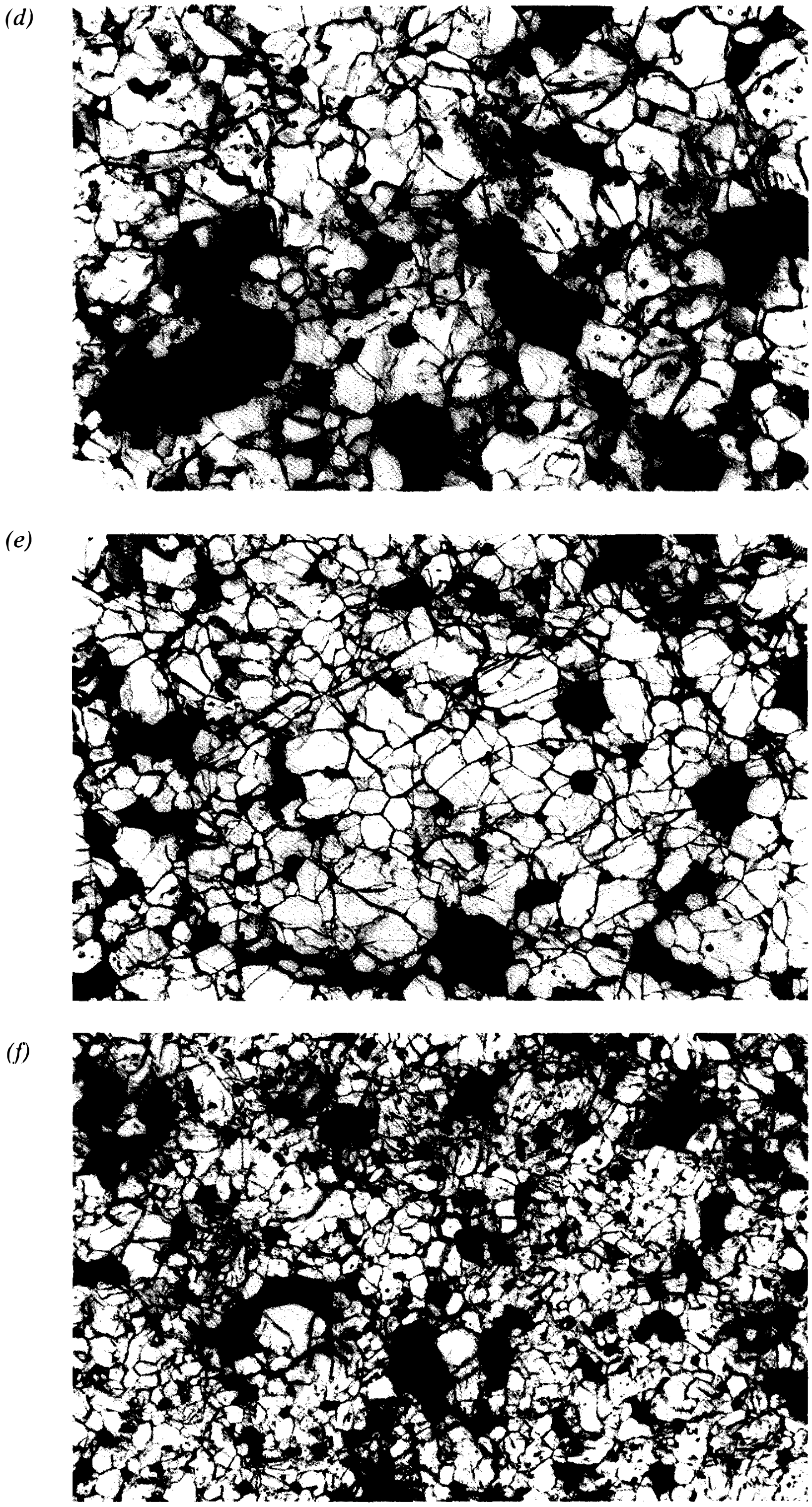

Fig. 1. Photomicrographs of primitive achondrites. Transmitted light.
d. Acapulco (acapulcoite), width=2.5 mm.
e. Y-791058,91-2 (silicate-rich portion of a IAB iron), width=2.5 mm.
f. ALH78230 (acapulcoite), width=2.5 mm.

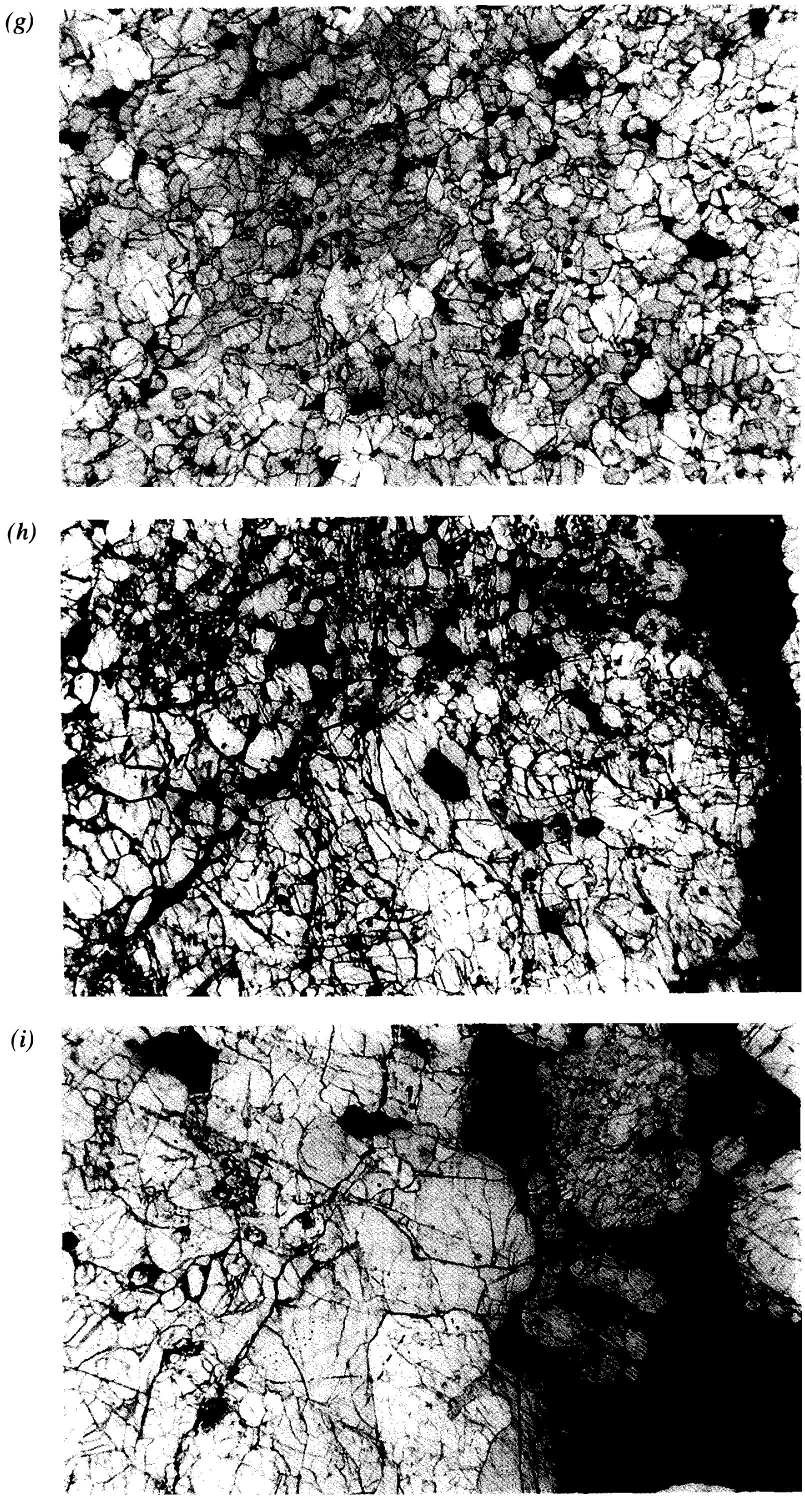

Fig. 1. Photomicrographs of primitive achondrites. Transmitted light.
g. Caddo County,B1A (IAB iron), width=8 mm.
h. Caddo County,B2A (IAB iron), width=8 mm.
i. Caddo County,B3A (IAB iron), width=8 mm.

Table 1. Modal abundances of minerals obtained from mineral distribution maps (vol%).

	Olivine	Opx[1]	Aug[2]	Plagioclace	Ca-Phosphate	Chromite	Troilite	FeNi-metal[3]	Schreibersite	Daubreelite
Acapulco (A)	25.2	41.1	2.5	14.8	1.21	0.82	8.7	5.7	0.01	0.00
ALH77081 (A)	27.9	38.7	7.3	14.2	0.42	0.94	3.9	6.6	0.00	0.00
ALH78230 (A)	28.4	37.7	5.3	13.6	0.52	0.85	6.9	6.7	0.00	0.00
Y8307 (A)	25.9	32.4	6.7	13.5	0.90	0.19	5.5	15.0	0.00	0.00
EET84302,28 (A/L)	17.7	38.6	0.5	15.2	0.04	0.00	0.2	27.2	0.62	0.00
Gibson (L)	27.3	41.9	6.3	3.3	0.00	0.09	0.3	20.8	0.07	0.00
MAC88177 (L)	48.7	44.1	1.9	0.0	0.03	0.00	4.1	1.1	0.00	0.00
Y74357 (L)	71.9	9.7	4.7	0.0	0.09	0.06	0.3	13.1	0.27	0.00
Y75274 (L)	20.3	50.5	0.4	2.3	0.00	0.00	0.0	25.3	1.23	0.00
Y791491 (L)	57.4	32.0	0.2	0.2	0.16	0.55	5.4	4.1	0.06	0.00
Y8002 (L)	31.7	43.7	1.7	10.0	0.01	0.04	0.3	12.2	0.25	0.00
Tierra Blanca (W)	27.6	32.7	0.2	10.2	0.09	0.02	3.8	25.5	0.03	0.00
Y74025 (W)	16.0	41.4	6.1	14.9	0.00	0.00	14.0	7.0	0.15	0.51
Y75305 (W)	5.8	36.5	0.4	8.6	0.01	0.12	9.2	39.0	0.02	0.29
Y8005 (W)	11.8	28.4	6.2	13.5	0.00	0.04	7.2	31.7	0.81	0.28
Y791058,91-2 (I)	24.8	40.9	2.1	17.6	0.28	0.01	4.1	10.2	0.09	0.00
Caddo Co. B1A (I)	26.0	39.9	5.3	20.4	0.21	0.03	4.3	3.7	0.09	0.00
Caddo Co. B2A (I)	9.7	11.9	18.8	34.3	0.85	0.01	8.1	16.0	0.34	0.00
Caddo Co. B3A (I)	9.6	11.8	24.8	35.8	0.00	0.00	1.2	16.4	0.49	0.00
Y75008 (H7)	18.4	36.3	2.7	4.7	0.37	1.46	7.2	29.0	0.00	0.00

1) orthopyroxene. 2) augite. 3) Including weathering procucts (Fe-hydroxide).

A = Acapulcoite, L = Lodranite, W = Winonaite, I = IAB iron and H7 = H7 chondrite.

Table 2a. Chemical compositions of orthopyroxene in primitive achondrites (wt%).

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	Total	*fe#*	Wo	En	Fs
Acapulco (A)	57.2	0.21	0.29	7.27	0.69	33.9	0.94	0.03	0.27	100.80	10.7	1.76	87.7	10.6
ALH77081 (A)	58.0	0.22	0.29	6.85	0.56	34.0	0.87	0.02	0.26	101.07	10.2	1.63	88.4	9.99
ALH 78230 (A)	57.9	0.21	0.30	6.90	0.58	33.9	0.91	0.02	0.26	100.98	10.2	1.70	88.2	10.1
ALH 81187 (A)	58.2	0.19	0.43	4.28	0.61	34.7	1.71	0.12	0.97	101.21	6.5	3.21	90.5	6.27
ALH 81261 (A)	57.8	0.19	0.29	6.76	0.54	33.8	0.88	0.02	0.24	100.52	10.1	1.66	88.4	9.92
Y8307 (A)	58.0	0.21	0.29	6.70	0.53	33.5	0.86	0.02	0.34	100.45	10.1	1.63	88.5	9.92
EET84302[1] (A/L)	57.8	0.22	0.49	5.54	0.52	33.9	1.32	0.04	0.48	100.31	8.4	2.50	89.3	8.19
Gibson (L)	58.6	0.18	0.40	3.81	0.53	35.8	1.06	0.02	0.27	100.67	5.7	1.98	92.5	5.53
MAC88177[1] (L)	55.7	0.15	0.60	8.15	0.54	32.1	1.75	0.05	0.48	99.52	12.5	3.60	84.2	12.2
Y74357[1] (L)	56.9	0.15	0.35	9.09	0.54	31.3	1.35	0.06	0.38	100.12	14.0	2.60	83.8	13.7
Y75274 (L)	58.0	0.28	0.40	2.80	0.42	36.7	1.47	0.04	0.43	100.54	4.11	2.69	93.3	4.00
Y791491 (L)	57.0	0.17	0.41	8.05	0.57	32.0	1.34	0.03	0.40	99.97	12.4	2.58	85.4	12.1
Y8002 (L)	57.3	0.22	0.35	2.55	0.40	36.4	1.37	0.03	0.43	99.05	3.78	2.53	93.8	3.68
Winona (W)	59.0	0.23	0.27	4.70	0.35	35.9	0.97	0.03	0.19	101.64	6.84	1.78	91.5	6.71
Tierra Blanca (W)	57.5	0.18	0.33	5.00	0.53	35.0	1.14	0.10	0.38	100.16	7.42	2.13	90.6	7.27
Y74025[2] (W)	58.2	0.04	0.33	1.62	0.26	38.7	0.98	0.00	0.07	100.20	2.29	1.75	96.0	2.25
Y75305[2] (W)	58.7	0.08	0.15	1.32	0.17	38.4	0.94	0.00	0.06	99.82	1.89	1.70	96.5	1.86
Y8005 (W)	60.0	0.17	0.21	1.45	0.52	38.1	0.86	0.02	0.17	101.50	2.10	1.57	96.4	2.07
Caddo County (I)	57.4	0.19	0.32	4.85	0.48	35.0	1.22	0.06	0.41	99.93	7.23	2.28	90.7	7.06
Y791058 (I)	58.5	0.25	0.22	4.29	0.44	36.3	0.80	0.02	0.20	101.02	6.22	1.47	92.4	6.13
Y75008 (H7)	57.3	0.10	0.51	10.53	0.47	29.4	2.07	0.08	0.78	101.24	16.8	4.0	79.9	16.1

1) Takeda *et al.* (1994). 2) Kimura *et al.* (1992). A = Acapulcoite, L = Lodranite, W = Winonaite, I = IAB iron and H7 = H7 chondrite.

Table 2b. Chemical compositions of augite in primitive achondrites (wt%).

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	Total	*fe#*	Wo	En	Fs
Acapulco (A)	55.6	0.53	0.79	2.96	0.36	17.7	21.7	0.69	1.30	101.63	8.59	44.7	50.6	4.75
ALH77081 (A)	54.9	0.58	0.82	2.74	0.33	18.1	21.4	0.01	1.45	100.33	7.81	43.8	51.8	4.39
ALH 78230 (A)	54.8	0.57	0.90	2.70	0.34	17.9	20.9	0.01	1.34	99.46	7.80	43.7	52.0	4.39
ALH 81187 (A)	55.1	0.55	1.00	1.83	0.35	18.8	20.6	0.01	1.83	100.07	5.17	42.7	54.4	2.96
ALH 81261 (A)	55.2	0.56	0.81	2.64	0.35	17.9	21.3	0.01	1.42	100.19	7.65	44.1	51.6	4.27
Y8307 (A)	53.3	0.54	0.79	6.37	0.27	16.4	20.3	0.75	1.33	100.05	17.9	42.2	47.5	10.3
EET84302[1] (A/L)	53.0	0.50	0.93	3.46	0.35	17.6	21.1	0.71	1.46	99.11	9.91	43.7	50.8	5.59
Gibson (L)	55.0	0.42	0.96	2.25	0.36	19.2	20.4	0.69	0.93	100.21	6.17	41.8	54.7	3.59
MAC88177[1] (L)	55.0	0.31	1.29	4.60	0.35	19.7	17.4	0.56	1.27	100.48	11.6	35.9	56.7	7.42
Y74357[1] (L)	55.0	0.31	0.94	3.94	0.31	17.5	20.0	0.79	1.44	100.23	11.2	42.1	51.4	6.48
Y75274 (L)	55.5	0.82	0.83	1.10	0.19	19.2	22.6	0.54	0.71	101.49	3.12	45.1	53.2	1.71
Y791491[1] (L)	54.1	0.45	1.01	3.27	0.23	17.8	21.3	0.80	1.20	100.16	9.35	43.8	50.9	5.25
Winona (W)	56.5	0.70	0.78	1.90	0.20	18.6	22.6	0.61	0.73	102.62	5.42	45.2	51.8	2.97
Tierra Blanca (W)	54.9	0.23	0.17	1.68	0.39	17.8	20.1	1.51	3.13	99.91	5.02	43.5	53.7	2.84
Y74025[2] (W)	54.8	0.75	0.71	0.51	0.06	19.4	23.2	0.42	0.15	100.00	1.46	45.9	53.3	0.79
Y75305[2] (W)	55.4	0.25	0.48	0.56	0.12	18.2	23.4	0.33	0.14	98.88	1.70	47.7	51.4	0.89
Y8005 (W)	53.9	1.00	1.01	1.39	0.24	18.3	22.1	0.61	0.66	99.21	4.09	45.5	52.3	2.23
Caddo County (I)	54.4	0.70	0.81	1.74	0.25	18.7	21.6	0.67	0.87	99.74	4.96	44.1	53.1	2.77
Y791058 (I)	55.1	0.60	0.84	1.85	0.31	18.4	22.1	0.69	1.14	100.03	5.35	45.0	52.1	2.94

1) TAKEDA *et al.* (1994). 2) KIMURA *et al.* (1992). A = Acapulcoite, L = Lodranite, W = Winonaite and I = IAB iron.

Table 2c. Chemical compositions of olivine in primitive achondrites (wt%).

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	Total	*fe#*
Acapulco (A)	38.4	0.07	0.30	11.4	0.62	46.7	0.03	0.01	2.94	100.47	12.0
ALH77081 (A)	40.9	0.01	0.01	10.2	0.51	49.4	0.01	0.01	0.03	101.08	10.3
ALH78230 (A)	40.7	0.01	0.03	10.0	0.52	49.3	0.03	0.01	0.02	100.62	10.2
ALH81187 (A)	42.2	0.01	0.02	3.97	0.47	54.7	0.02	0.01	0.04	101.44	3.91
ALH81261 (A)	40.8	0.02	0.01	9.81	0.52	49.3	0.02	0.01	0.10	100.59	10.0
Y8307 (A)	41.4	0.01	0.01	10.5	0.49	48.6	0.02	0.01	0.05	101.09	10.8
EET84302 (A/L)	41.2	0.01	0.02	8.20	0.45	50.4	0.03	0.01	0.03	100.35	8.36
Gibson (L)	42.1	0.01	0.00	2.94	0.39	54.9	0.04	0.00	0.04	100.42	2.92
MAC88177[1] (L)	40.5	0.01	0.03	12.8	0.48	46.5	0.01	0.01	0.01	100.35	13.4
Y74357[1] (L)	41.3	0.00	0.02	7.59	0.52	50.8	0.02	0.01		100.26	7.73
Y75274 (L)	41.1	0.01	0.00	3.93	0.37	54.4	0.02	0.00	0.03	99.86	3.89
Y791491 (L)	40.4	0.01	0.00	11.0	0.49	48.0	0.05	0.01	0.03	99.99	11.4
Y8002 (L)	41.1	0.01	0.01	3.48	0.36	54.2	0.02	0.00	0.05	99.23	3.47
Winona (W)	41.9	0.01	0.00	3.75	0.31	55.2	0.01	0.00	0.02	101.20	3.67
Tierra Blanca (W)	41.4	0.00	0.03	5.57	0.70	52.5	0.02	0.04	0.02	100.28	5.62
Y74025 (W)	41.5	0.00	0.01	1.81	0.29	56.2	0.00	0.00	0.02	99.83	1.78
Y75305 (W)	42.5	0.00	0.00	1.75	0.17	55.0	0.00	0.00	0.02	99.44	1.75
Y8005 (W)	42.1	0.01	0.06	2.15	0.34	56.1	0.01	0.00	0.02	100.79	2.11
Caddo County (I)	41.8	0.03	0.01	4.05	0.41	54.3	0.02	0.00	0.06	100.68	4.02
Y791058 (I)	42.0	0.02	0.01	4.82	0.39	54.1	0.01	0.01	0.02	101.38	4.76
Y75008 (H7)	40.2	0.03	0.01	17.3	0.42	42.5	0.02	0.00	0.04	100.52	18.6

1) Takeda *et al.* (1994). A = Acapulcoite, L = Lodranite, W = Winonaite, I = IAB iron and H7 = H7 chondrite.

Table 2d. *Chemical compositions of plagioclase of primitive achondrites (wt%).*

	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total	An	Ab	Or
Acapulco (A)	65.7	0.06	22.2	0.13	0.01	3.32	9.61	0.72	101.75	15.4	80.6	3.99
ALH77081 (A)	66.8	0.05	22.1	0.25	0.01	3.00	9.08	0.76	102.05	14.8	80.8	4.45
ALH78230 (A)	65.4	0.04	21.8	0.39	0.06	2.84	9.00	0.77	100.30	14.2	81.3	4.56
ALH81261 (A)	66.1	0.06	22.2	0.14	0.01	3.06	9.12	0.81	101.50	14.9	80.4	4.68
ALH81187 (A)	63.0	0.06	22.3	1.02	0.02	3.78	9.81	0.26	100.25	17.3	81.3	1.43
Y8307 (A)	64.0	0.04	21.1	1.54	0.02	2.98	8.82	0.83	99.33	15.0	80.1	4.95
EET84302 (A/L)	63.6	0.04	23.3	0.12	0.03	4.76	9.17	0.36	101.38	21.9	76.2	1.95
Gibson (L)	65.1	0.03	22.8	0.23	0.01	4.11	8.32	0.64	101.24	20.6	75.5	3.83
Y8002 (L)	60.3	0.06	24.5	0.07	0.01	6.09	8.40	0.31	99.74	28.1	70.2	1.71
Y75274 (L)	62.8	0.07	23.3	0.98	0.01	5.33	8.12	0.32	100.93	26.1	72.0	1.84
Winona (W)	66.8	0.07	22.4	0.38	0.00	3.43	8.67	0.67	102.42	17.2	78.8	4.02
Tierra Blanca (W)	65.2	0.00	21.6	0.26	0.02	2.84	10.3	0.55	100.77	12.8	84.3	2.93
Y74025 (W)	64.5	0.01	23.1	0.28	0.01	4.23	9.82	0.33	102.28	18.9	79.3	1.77
Y75305 (W)	62.8	0.01	23.8	0.35	0.12	5.51	8.77	0.23	101.59	25.5	73.3	1.29
Y8005 (W)	65.8	0.04	21.5	0.43	0.01	2.53	10.8	0.48	101.59	11.2	86.3	2.54
Caddo County (I)	64.1	0.07	22.5	0.09	0.01	3.10	9.76	0.48	100.11	14.5	82.8	2.69
Y791058 (I)	66.0	0.07	22.3	0.07	0.01	3.21	9.06	0.70	101.42	15.7	80.3	4.06

A = Acapulcoite, L = Lodranite, W = Winonaite and I = IAB iron.

Table 2e. Chemical compositions of Fe-Ni metal (kamacite) of primitive achondrites (wt%).

	Co	Fe	Ni	P	Total
Acapulco (A)	0.64	92.7	7.51	0.01	100.86
ALH77081 (A)	0.59	93.8	6.47	0.01	100.87
ALH78230 (A)	0.56	93.8	6.63	0.00	100.99
ALH81187 (A)	0.54	94.6	5.75	0.00	100.89
ALH81261 (A)	0.59	93.0	6.76	0.00	100.35
Y8307 (A)	0.61	93.5	6.92	0.00	101.03
EET84302[1] (A/L)	0.60	92.6	6.16	0.07	99.43
Y74357[1] (L)	0.45	94.9	4.66	0.08	100.09
Y75274[1] (L)	0.50	94.6	4.95	0.03	100.08
Y8002 (L)	0.50	93.9	5.47	0.06	99.93
Tierra Blanca (W)	0.65	92.6	5.77	0.00	99.02
Y74025 (W)	0.65	93.2	6.32	0.00	100.17
Y75305 (W)	0.64	92.6	6.87	0.00	100.11
Y8005 (W)	0.52	94.0	6.33	0.00	100.85
Caddo County (I)	0.57	93.6	6.68	0.01	100.86
Y791058 (I)	0.55	93.0	6.37	0.00	99.92
Y75008 (H7)	0.64	93.5	6.94	0.05	101.13

1) After TAKEDA *et al.* (1994).

A = Acapulcoite, L = Lodranite, W = Winonaite, I = IAB iron and H7 = H7 chondrite.

Y-791058

PTS Y-791058,51-2 is metal-rich (YANAI, 1992; TAKEDA *et al.*, 1994), whereas Y-791058,91-2 is a silicate-rich PTS (Fig. 1e) . Silicates are fine-grained (about 0.1–0.3 mm) and clear. The modal abundances of minerals of PTS Y-791058,51-2 are: metal-sulfide-Fe-hydroxide 82 vol%, Ol 4, Opx 8, Plag 6, Aug 0.1 and trace amounts of whitlockite (TAKEDA *et al.*, 1994). The modal abundances of minerals in PTS Y-791058,91-2 obtained from the mineral distribution map (Fig. 2c) are shown in Table 1. It is very similar to acapulcoites, although it is slightly richer in Plag (17.6 vol%). PTS Y-791058,91-2 is also similar to acapulcoites in texture. Plag is distributed homogeneously in PTS Y-791058,91-2 but Aug is distributed locally. The *fe#* of Opx is 6.2 and that of Ol is 4.8.

Other samples

The other samples studied in this paper include five acapulcoites (Acapulco, ALH77081,4, ALH78230,51-2, ALH81187,16 and ALH81261,14), seven lodranites (Gibson, EET84302,28, Y-74357,62-1, Y-75274,81-2, Y-791491,61-2, Y-8002,51-2 and

MAC88177,17), four winonaites (Tierra Blanca, Winona, Y-74025,52-4 and Y-75305,52-2) and IAB iron (Caddo County,B1A,B2A,B3A) and one H7 chondrites (Y-75008,2-3). Mineral distribution maps for these meteorites were made except for ALH81187 and ALH81261. The modal abundances of minerals obtained from these mineral distribution maps are shown in Table 1. The chemical compositions of minerals are shown in Tables 2a–e.

Acapulco (Palme *et al.*, 1981; Zipfel *et al.*, 1995) is coarser-grained (up to about 0.4 mm across) than ALH77081, ALH78230 (Fig. 1f) and ALH81261 (up to about 0.25 mm across). There are oriented dusty inclusions in Opx grains in Acapulco. ALH81187 has smaller *fe#*s of silicates than other acapulcoites (Tables 2a–c).

EET84302,28 includes considerable amounts of Ca-Al-rich minerals, and it contains large and complex-shaped metal grains. The modal abundances of minerals in EET84302,19 (Takeda *et al.*, 1994) is much different from those of EET84302,28. EET84302,28 also includes much larger amounts of Fe-Ni metal than other lodranites and acapulcoites, and the Fe-Ni metal grains have unique complex shapes (Fig. 1b).

The modal abundances of minerals in Winona was obtained only about silicates and Ca-phosphates, because Winona contains much weathering products. Y-74025 and Y-75305 contains daubreelite. The large metallic grains in Y-75305,52-2 nearly enclose a cluster of silicate grains (Fig. 2d). Tierra Blanca has larger *fe#*s of silicates than other winonaites (Tables 2a–c).

Three PTSs of Caddo County (B1A,B2A,B3A) which are parallel to the cut slab surface, 5 cm×3 cm of the original Caddo County sample (Takeda *et al.*, 1997) were used to obtain modal abundances. The PTSs, B1A (Fig. 1g), B2A (Fig. 1h) and B3A (Fig. 1i) represent three chemically distinct areas. Existence of basalt with gabbroic texture is recognized in PTSs, B2A and B3A. PTS Caddo County B1A (about 16.7 mm×15.3 mm) is a Mg-rich area in the X-ray elemental distribution map (Takeda *et al.*, 1997). The area is finer-grained (0.2–1.5 mm in size) than B3A, and Opx and Ol are the most abundant minerals, and Plag and Aug in much smaller amounts, filling interstices of grain boundaries of the mafic silicates together with troilite and Fe-Ni metal, and minor chromite. In some areas, vein-like Plag enclosing also elongated Aug are extended from the fine-grained mafic silicate-rich regions. The modal abundnces of minerals of B1A are similar to those of Y-791058,91-2 (silicate-rich PTS). PTS Caddo County,B2A has much larger Plag showing a poikilitic texture including rounded mafic silicates. Fine networks of metal distribute in some Plag-rich regions. PTS Caddo County,B3A represents an area adjacent to metal and consists of Aug crystals up to 1 mm in diameter set in much larger Plag crystals. The finer-grained region of PTS ,B1A has very similar modal abundances of minerals to acapulcoites (Table 1). The Y-75008 H7 extensively recrystallized chondrite was studied for comparison with primitive achondrites.

3.2. *Modal abundances of minerals*

Modal abundances of minerals of twenty PTSs obtained from mineral distribution maps are summarized in Table 1. The mineral distribution maps of Y-8005,51-3,Y-

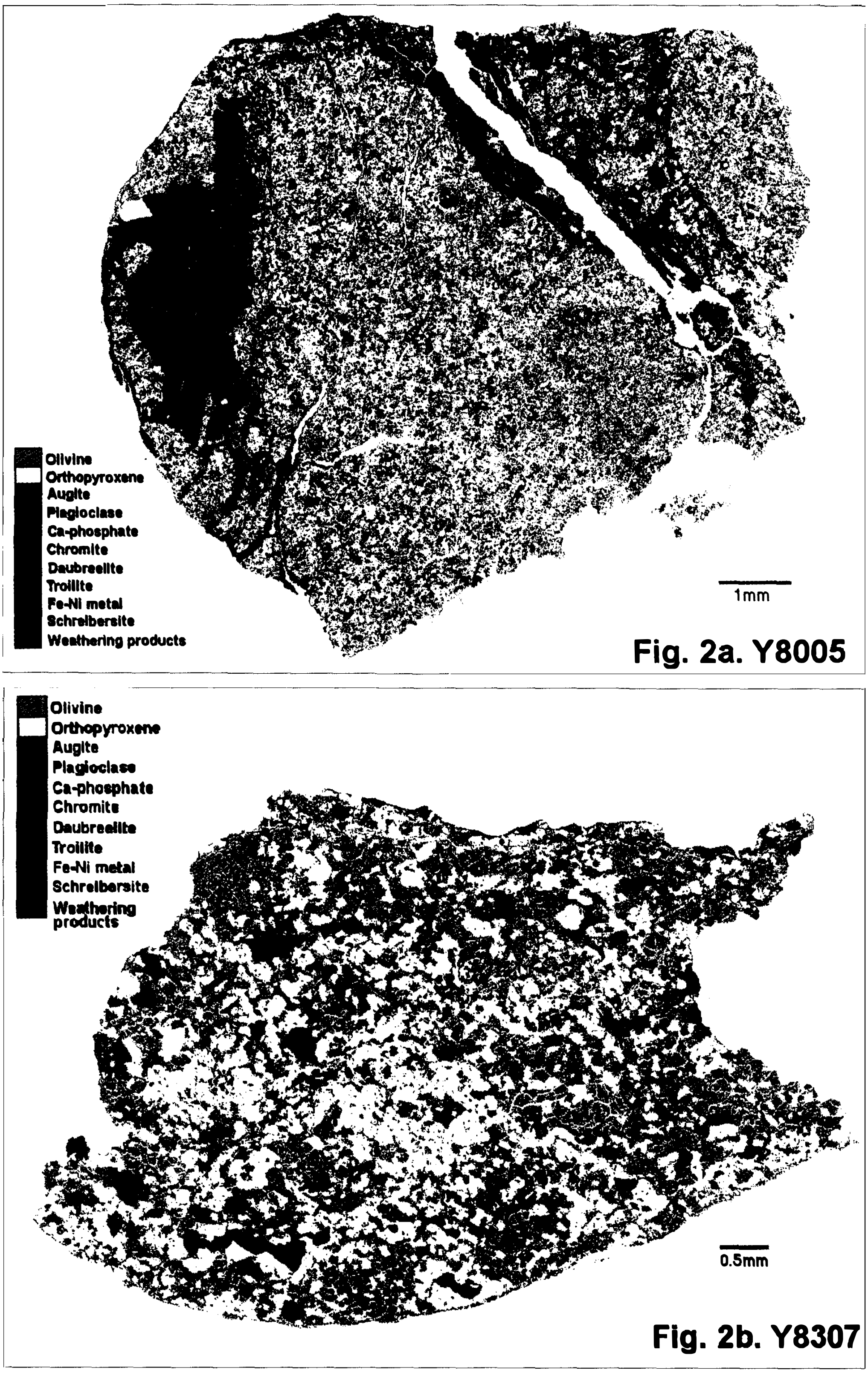

Fig. 2. Mineral distribution maps of primitive achondrites.
a. Y-8005 (winonaite). b. Y-8307 (acapulcoite).

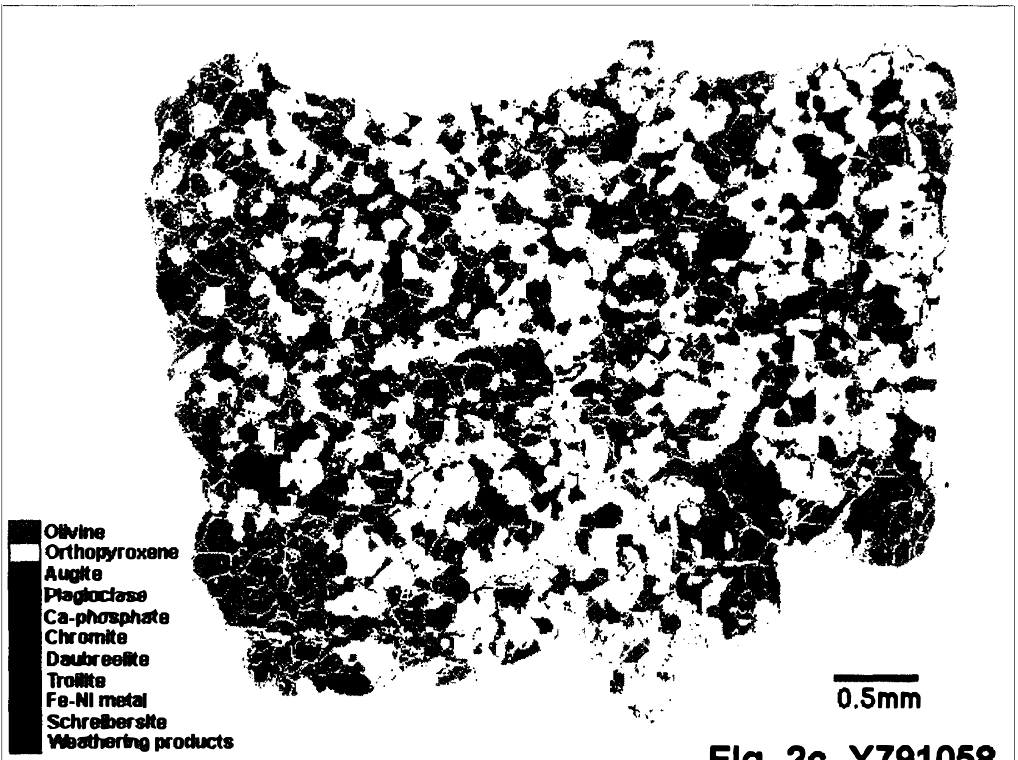

Fig. 2c. Y791058

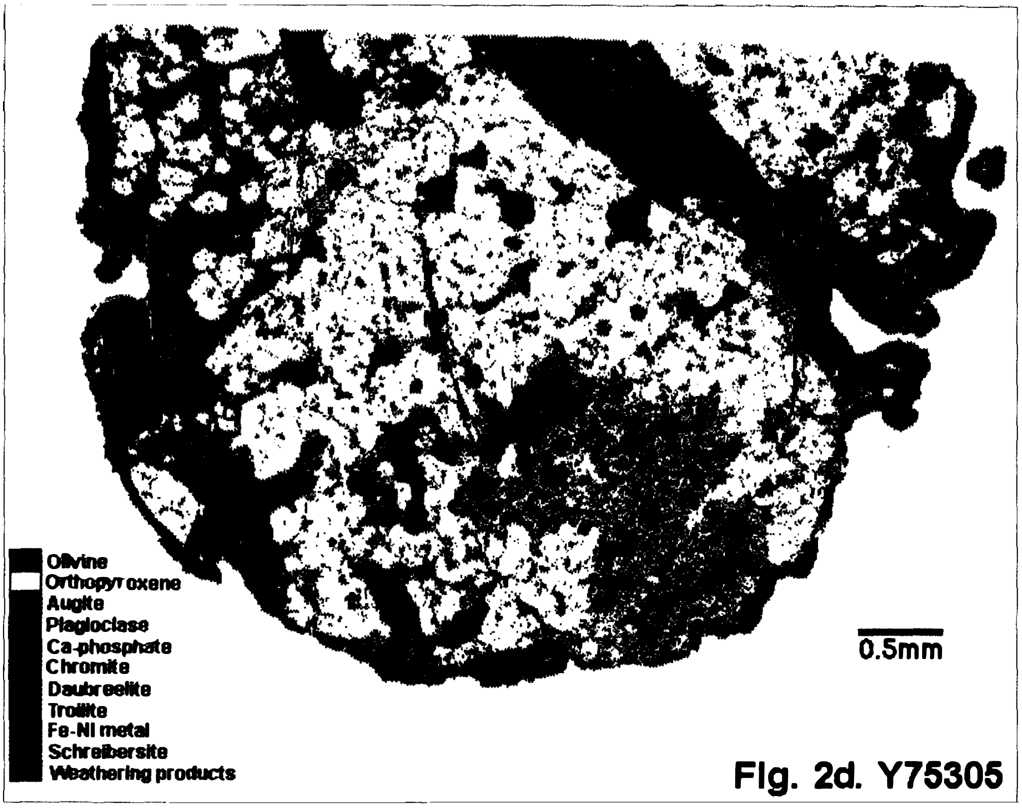

Fig. 2d. Y75305

Fig. 2. (continued).
c. Y-791058,91-2 (silicate-rich portion of a IAB iron).
d. Y-75305 (winonaite).

8307,51-2, Y-75305,52-2, and Y-791058,91-2, are shown in Figs. 2a–d. The volume percentage of opaque minerals varies from 5.2% (MAC88177) to 82% (Y-791058 metal-rich PTS).

Because the modal abundances of Fe-Ni and Fe-bearing sulfide and oxide are so variable, the mineral assemblages of silicate and phosphate portions of primitive achondrites are plotted in the Opx-Ol-(Plag+Aug) pseudo-ternary diagram (Fig. 4). The previous investigations (*e.g.*, Prinz *et al.*, 1983) used (Opx+Aug) component as a parameter to indicate differentiation trend. Instead, we combined Aug with Plag to see where Ca-Al-rich melt was concentrated.

4. Discussion

4.1. Modal abundances of minerals

Modal abundances of minerals of twenty PTSs obtained by CMA are summarized in Table 1. They are also plotted graphically in Figs. 3 and 4. Y-8307 is almost identical to ALH77081 and ALH78230 and is less similar to Acapulco. Y-8005 can be classified as a winonaite on the basis of mineral chemistry. The distribution of opaque minerals of Y-8005 is more similar to Y-75305 than Y-74025.

Y-8005, Y-8307 and Y-75008 fall in the area of acapulcoites and winonaites in the Opx-Ol-(Plag+Aug) pseudo-ternary diagram (Fig. 4). Winonaites generally tend to deviate from chondritic assemblages in the direction away from the Opx-Ol join, but Tierra Blanca is closer to the Opx-Ol join than other winonaites. Tierra Blanca is poorer in Ca-rich materials and slightly richer in Ol than other winonaites. The modal abundances of minerals of some selected parts of the PTSs of Caddo County, B1A (coarser-grained region (CR) and finer-grained region (FR)), B2A (region 1 (R1) and R2), B3A (R1, R2 and R3), EET84302,19 (chromite-rich region (C) and metal-rich region (M) (Takeda *et al.*, 1994)), are added in Fig. 4. There are considerable heterogeneities in each PTSs of Caddo County and EET84302,19. Caddo County, B1A FR is plotted at the region of acapulcoites. Gibson, Y-8002 and Tierra Blanca fall near the center of this diagram. Figure 4 clearly shows the differentiation trend of the AL group. Most lodranites plot towards lower base line between Opx and Ol. The variation of Opx/Ol ratio of these lodranites may mainly be due to the fact that these lodranite PTSs are not large in comparison with coarser grain sizes of the Opx and Ol crystals in these PTSs. Many acapulcoites are plotted above the H7 position. Most of the primitive achondrites are distributed near the bisector of the (Plag+Aug) corner. The samples which fall near the corner of Plag+Aug, can be interpreted as crystallization product of low-melting component, while those samples which fall near H-chondrites can be taken as the product of recrystallization of the chondritic materials. The samples fall near the Opx-Ol line can be taken as recrystallization product from residue of partial melt.

4.2. Classification of primitive achondrites

ALH77081, ALH78230 and ALH81261 resemble each other in texture and chemical and mineralogical compositions (Tables 2a–e). These meteorites can be taken as typical acapulcoites because they can be regarded as fine-grained recrystallized materi-

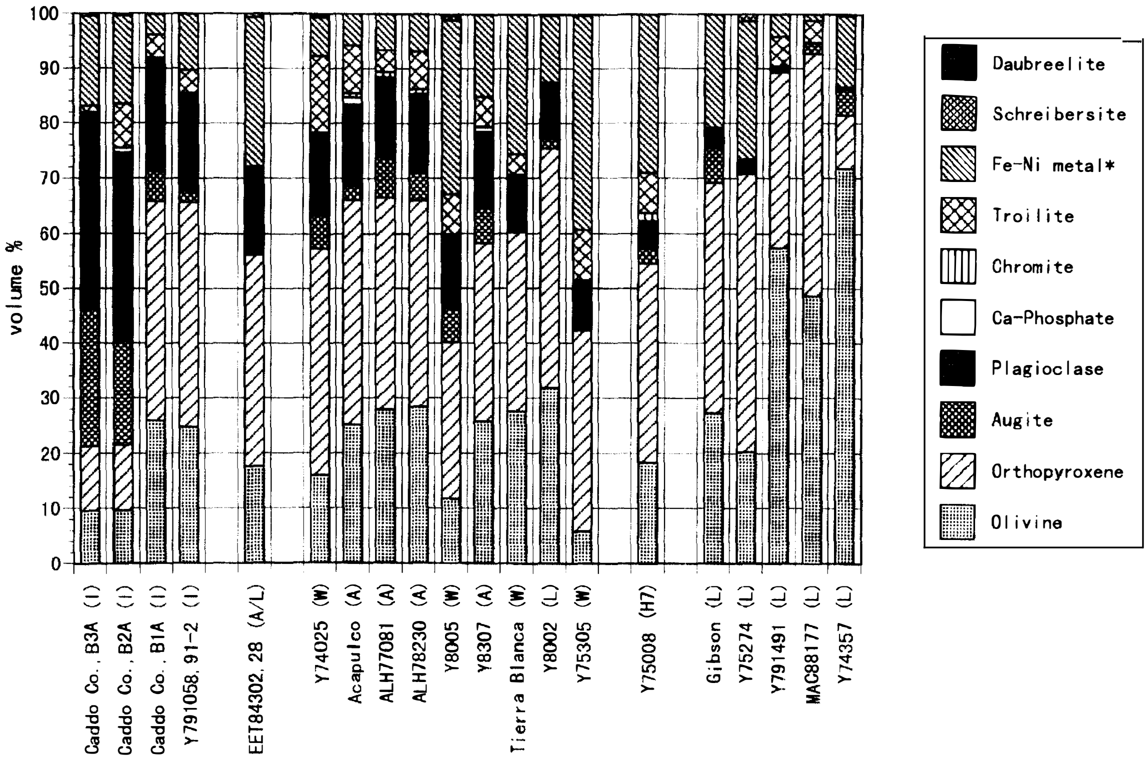

Fig. 3. Modal abundances of minerals of twenty PTSs, in order of decreasing percentages of plagioclase.

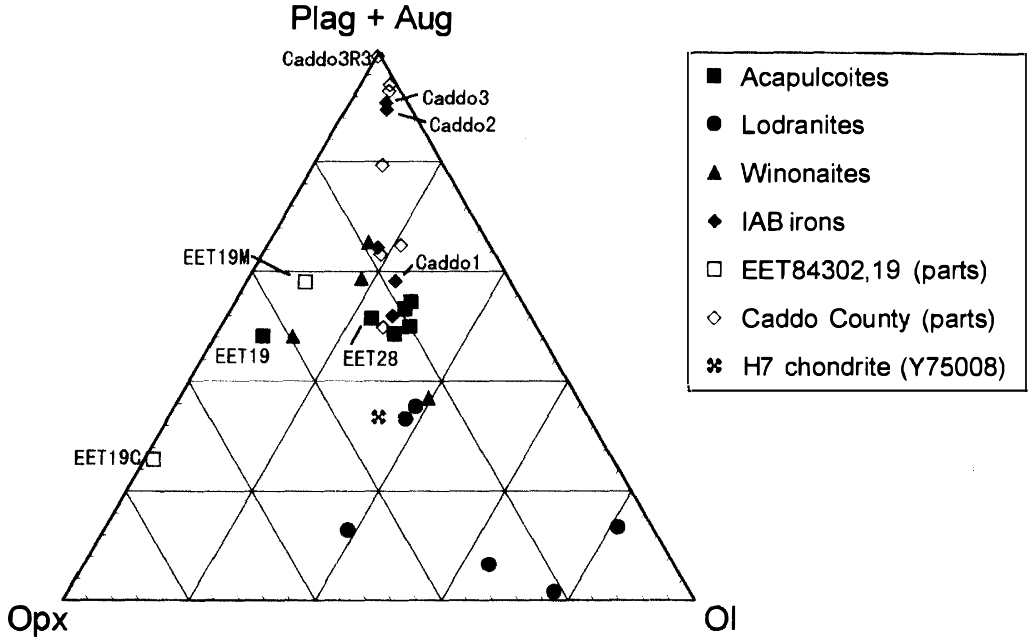

Fig. 4. The mineral assemblages of silicate portions normalized by Y-75008 plotted in an Opx-Ol- (Plag+Aug) daiagram. (Caddo1=Caddo County,B1A, Caddo2=Caddo County,B2A, Caddo3=Caddo County,B3A, Caddo3R3=Region 3 of Caddo County,B3A, EET19=EET84302,19, EET19C=chromite-rich region and EET19M=metal-rich region of EET84302,19 and EET28=EET84302,28). Data for EET84302,19 and Y-791058,51-2 are from Takeda *et al. (1994).*

als of near chondritic composition. Acapulco is slightly different from them in texture and compositions of silicates and metal volume percentage. Thus, Acapulco is not a typical acapulcoite. Modal abundances of minerals and chemical compositions of minerals of Y-8005 and Y-8307 show that Y-8005 is a winonaite and Y-8307 is an acapulcoite. ALH81187 and EET84302 have obviously different textures from other acapulcoites and are also different in composition. The small *fe#* of Ol and Opx in ALH81187 suggests that ALH81187 is more reduced than other acapulcoites. EET84302 was originally classified as a lodranite because of its coarse-grained texture, but the silicate portions of the two PTSs plot at farther points from lodranite region than other acapulcoites in Fig. 4. However, a region next to the chromite-rich area is like an Opx-rich lodranite (Takeda *et al.*, 1994). Certainly, it is difficult to classify such heterogeneous meteorite, but EET84302 has much chemical affinity to acapulcoites than to lodranites or Plag-Aug-rich materials. It is not an ordinary acapulcoite nor an ordinary lodranite. We believe that the amount of Ca-Al-rich minerals is more important factor to distinguish acapulcoites from lodranites, so we call EET84302 an acapulcoite.

Large amounts of Plag-Aug-rich materials were found in Caddo County, B2A and B3A. The discovery of Plag-Aug-rich materials such as Caddo County B2A and B3A tempts us to give a new sub-group name to the Plag-Aug-rich material. However, introduction of the new name may introduce further confusion in the classification scheme of primitive achondrites, so we are resisting this temptation for the time being.

4.3. Formation processes of primitive achondrites

4.3.1. Heterogeneous distributions of materials

The mineral distribution maps and modal abundances of minerals plotted in Fig. 4 show that the textures and modal abundances vary on a local scale, within a few cm. Gabbroic materials were found not far from the winonaite-like region (Caddo County, B1A) in the Caddo County slab sample. There are also metal-rich areas near these areas in the slab. These facts imply that the separation mechanisms may not have been too efficient in the WI parent body. We emphasize that such heterogeneous assemblages of materials are not due to reassemblage of clastic materials of different textures and mineral assemblages. The transition of one area to another takes place in a continuous manner, which can be best explained by a petrological process, rather than a mechanical reassembly of different clasts.

Acapulcoites and lodranites are thought to come from the same parent body on the basis of the oxygen isotopic compositions (Clayton *et al.*, 1992). The boundary between acapulcoites and lodranites is not clear and may be gradational. There may be no single explanation for the variety of acapulcoites and lodranites. The variety of the AL group suggests that there are primitive achondrites with complementary compositions of lodranites that have not been found yet. Although Caddo County comes from a separate parent body, meteorites similar to Caddo County B2A and B3A can be considered as a candidate of such complementary materials. The sample plotted near the Opx-(Plag+Aug) line is EET84302,19. The existence of EET84302 suggests that there may be more complementary meteorites to lodranites.

Hiroi *et al.* (1993) proposed a stony-iron model for S asteroids, which assumes that a few domains of various primitive achondrites are embedded in a Fe-metal matrix. In view of the observed variations in compositions and textures of primitive achondrites, the parent bodies of primitive achondrites are seemed to have local heterogeneity in finer scale than envisioned by Hiroi *et al.* The fine-grained regions of the parent bodies are acapulcoite-like and the coarse-grained regions depleted in Plag are lodranite-like. Iron meteorites with SI may also exist in the AL parent body if the Fe-Ni-S eutectic melt is concentrated locally. Such material has been recovered recently from Antarctica (T. McCoy, pers. commun.,1997), but its origin is not determined. The local heterogeneity of materials in the AL parent body can explain the variety of abundances of minerals found in both meteorites and S asteroids.

On the basis of the presence of coarser mafic mineral inclusions in fine-grained matrix in Winona, Benedix *et al.* (1996) proposed a destruction and reassembly model. A similar texture found in Y-8307 is not as pronounced as that of Winona and no relationship can be seen between the distribution of coarse grained materials and those of Aug and Plag, and the fault-like lines. The texture of Y-8307 does not support the reassembly model. The complex shapes of metal cannot be interpreted as clasts of metallic cores. These coarse-grained portions of silicates can be interpreted as growth of coarser-grained mafic silicates in expense of fine-grained materials, using larger grains in the original chondrites as nucleus crystals. We do not need to invoke reassembly of differentiated clasts of silicate material as was proposed by Benedix *et al.* (1996). The textures and materials in mesosiderites or howardites are those produced by brecciation and mixing. We did not find such texture in Caddo County at least in our thin sections. If brecciation and mixing had occurred, we could see more genetically unrelated materials in the PTSs. The heterogeneous distribution of materials in EET84302 is in line with the idea that local heterogeneity of materials in the parent body can explain the variety of primitive achondrites (Takeda *et al.*, 1994).

We assume that AL and WI were formed by common process. The existence of Caddo County is not direct evidence to show there was not explosive volcanism, but we suggest that Caddo County-like materials can exist in the AL group. Takeda *et al.* (1994) found a region enriched in plagioclase, augite and metal in EET84302, and McCoy *et al.* (1997b) found subsequently such basaltic material in LEW86220, but they interpreted it differently. We believe that our model can explain more observations than other models.

4.3.2. Common processes of early differentiation in primitive achondrite bodies

There are some noticeable differences between the AL and WI groups. The mafic silicate-rich lodranite-like area is conspicuously missing in the WI group, and the iron-meteorite-like materials are missing in the AL group. However, these differences may be the result of problems in sampling a large parent body, and metal-rich trends observed in EET84302 suggest extension of the trend will lead to the Caddo County-like materials.

By combining these two groups, the entire picture of the parent body can be reconstructed. From an ideal picture reconstructed from some members of the AL/WI group, a formation and evolution mechanism of these meteorite groups has been proposed as the most basic differentiation process of planetesimals from primitive source materials. This mechanism involves segregation and migration of partial melts such as Ca-, Al-rich silicate melt and Fe-Ni-S eutectic melt from chondritic materials in the AL group.

The origin of primitive achondrites can be explained by local heterogeneity of materials in the parent bodies, with the variation in extent of differentiation from recrystallized chondrite to segregation of iron meteorite plus plagioclase-augite assemblage leaving lodranite-like mafic silicates behind. Such processes are the most basic form of differentiation of primitive source materials.

5. Conclusions

(1) Mineralogical characterization of winonaites and silicate inclusions in IAB iron meteorites and other primitive achondrites revealed that boundaries between the subgroups cannot be clearly defined, but instead are gradational. Each sample represents one picture of continuum of chemical and mineralogical variations.

(2) General features of these variations include large difference in the silicate/metal abundance and in the plagioclase and augite abundance. The olivine/Opx ratio does not show a large variation except for some lodranites.

(3) Primitive achondrites that include Ca-phosphate and have mafic silicates with *fe#* >10 do not include schreibersite. Primitive achondrites that include schreibersite and that have mafic silicates *fe#* <10 do not include Ca-phosphate. Those with much smaller *fe#*s include daubreelite. Such trends can be explained by the oxidation-reduction condition.

(4) The mineral distribution of primitive achondrites is variable. Investigations of more than one PTSs of the same meteorite reveal that there is also considerable heterogeneity of the mineral distribution in a smaller scale, within one meteorite or even within one PTS.

(5) The origin of primitive achondrites can be explained by local heterogeneity of materials in the parent bodies with the variation trend from recrystallized chondrite to segregation of iron meteorite plus plagioclase-augite assemblage leaving lodranite-like mafic silicates behind. Such processes are the most basic form of differentiation of primitive source materials.

(6) The above facts cannot be explained by a simple equilibrium partial melting model proposed by previous investigators.

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