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PETROLOGICAL AND GEOCHEMICAL STUDY OF THE YAMATO-74359 AND YAMATO-74360 ACHONDRITES

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Abstract: Two Antarctic achondrites, Yamato(Y)-74359 and Y-74360, are very similar in bulk chemical compositions to the silicate portions of H chondrites, but the siderophile elements are extremely depleted in comparison to those of H chondrites. They consist of olivine, pyroxene and cryptocrystalline feldspar with minor amounts of chromite, kamacite, and troilite, and the chemical compositions of the constituent minerals are similar to those in H chondrites. Taking into consideration that the two achondrites have oxygen isotopic compositions typical of H chondrites, they were produced from H chondrites or the precursors of H chondrites. Chondrules are not observed, and the texture of the two achondrites is similar to one another, although Y-74360 is coarser-grained than Y-74359. Olivine occurs as euhedral or subhedral grains, mostly smaller than 100 microns in diameter, and they show slight chemical zoning, from magnesian cores (Fo_{82-83}) to ferroan rims (Fo_{80-78}). Orthopyroxene occurs as euhedral grains, larger than olivine grains, and also shows slight chemical zoning, from Ca-poorer magnesian cores to Ca-richer ferroan rims. Clinopyroxene occurs as rims of orthopyroxenes and shows remarkable chemical zoning continuously from pigeonitic interiors to augitic rims. Cryptocrystalline feldspar occurs in interstitial spaces between olivine and/or pyroxene, and seems to have crystallized in interstitial liquids in a rapid cooling condition. The cryptocrystalline feldspars in Y-74359 are chemically heterogeneous, classified into three groups, albite ($An_{1-4}Ab_{94-96}Or_{2-4}$), anorthoclase ($An_{6-10}Ab_{79-86}Or_{4-15}$), and intermediate alkali feldspar ($An_{1-2}Ab_{51-56}Or_{42-47}$), and occur in different portions of the thin section. The two achondrites seem to have formed by partial melting from heterogeneous silicate precursors of unequilibrated H chondrites.

1. Introduction

Japanese Antarctic meteorite collection includes more than ten unusual meteorites which are classified as "unique type" in a catalog (YANAI and KOJIMA, 1987), and these are being studied by a consortium (Leader: Prof. I. KUSHIRO). Two of these "unique" meteorites, Yamato-74359 (Y-74359) and Yamato-74360 (Y-74360), are very small achondrites (1.5 g and 3.3 g, respectively) and are very similar in overall texture to one another. The mineralogy of the two achondrites is similar to that of equilibrated H chondrites, but a few serious differences are observed between them in addition to the absence of chondrules in the former; the former extremely depletes in Fe-Ni metal and troilite in comparison to the latter, the former shows "igneous textures" although the latter does metamorphic textures, and the olivine and pyroxene in the former show normal chemical zoning in contrast to the homogeneous mineral composition of the latter. In this paper a petrological and geochemical study of the two achondrites is carried out as part of a consortium study, and their genetical relationship to H chondrites is discussed.

2. Analytical Methods

Each thin section of the two achondrites (Y-74359, 51–2 and Y-74360, 51–2) was used for microscopic observation, mineralogy, and major element chemical composition. The constituent minerals were analyzed using an electron-probe microanalyzer (EPMA), using the correction methods of BENCE and ALBEE (1968) for silicates and of standard ZAF methods for sulfides and metals. The representative chemical compositions of the constituent minerals in both achondrites are tabulated in Tables 1 and 2.

Major element chemical compositions of the bulk samples were measured on each thin section using a defocussed beam, about 50 microns in diameter, of the EPMA with the correction methods of IKEDA (1983). Y-74359 is heterogeneous in alkalis and consists mainly of K-rich and K-poor portions, and the chemical compositions of each portion were obtained separately. The bulk compositions of Y-74360 and K-rich and K-poor portions of Y-74359 are shown in Table 3.

The trace element contents of the Y-74360 achondrite were obtained by INAA methods using a powdered sample of about 50 mg. The analytical methods are the same as those detailed in IKEDA *et al.* (1990). The results are given in Table 4.

3. Petrography and Mineralogy

The petrography and mineralogy of the Y-74359 and 74360 achondrites are very similar to one another, although the former is finer-grained than the latter. The overall textures of the two achondrites (Fig. 1) resemble those of porphyritic olivine-pyroxene chondrules in unequilibrated ordinary chondrites although cryptocrystalline feldspar occurs in the two achondrites instead of clean glasses in the chondrules. The achondrites consist of olivine, orthopyroxene, clinopyroxene, and cryptocrystalline feldspar with minor amounts of chromite, troilite, and Fe-Ni metal. Olivine and orthopyroxene are predominant.

Olivine in Y-74359 occurs as euhedral or subhedral grains, and its size ranges mainly from 10 to 50 microns across. Sometimes olivine is included in large orthopyroxene grains. Orthopyroxene occurs as euhedral laths or rectangular grains, and its size ranges from 10 to 100 microns. Clinopyroxene occurs as rims on orthopyroxene grains. Chromite occurs in interstitial spaces between olivine and/or pyroxene grains, and its size ranges from 10 to 50 microns across. Fe-Ni metal and troilite occur in small amounts, and they are only a few grains, from 5 to 50 microns across. Feldspar is cryptocrystalline and fills the interstitial spaces between olivine

Table 1. Representative chemical compositions of silicates and oxides in the Y-74359 and Y-74360 achondrites.

	Y-74359								Y-74360					
	Ol	Opx	Pig	Aug	Ab	Anor	Or	Chm	Ol	Opx	Pig	Aug	Ab	Chm
SiO_2	38.07	54.59	54.72	53.04	68.73	70.08	68.66	0.03	38.44	55.80	54.69	51.52	67.75	0.00
TiO_2	0.00	0.00	0.09	0.24	0.26	0.24	0.34	1.99	0.00	0.00	0.08	0.82	0.52	1.13
Al_2O_3	0.00	0.42	0.74	1.15	18.46	18.40	17.89	7.35	0.00	0.28	0.36	2.67	18.70	8.46
Cr_2O_3	0.00	0.84	0.88	1.28	0.00	0.00	0.00	56.39	0.04	0.97	1.02	2.07	0.00	58.64
FeO	17.65	11.31	10.51	5.29	0.16	0.07	0.59	27.39	18.69	10.28	11.18	4.99	0.32	25.50
MnO	0.56	0.55	0.63	0.47	0.00	0.10	0.00	0.78	0.61	0.24	0.62	0.38	0.00	0.70
MgO	42.14	30.26	27.20	18.99	0.00	0.00	0.05	4.55	41.72	30.78	27.47	16.25	0.26	5.30
CaO	0.08	1.65	4.93	18.61	0.46	1.58	0.27	0.03	0.00	1.56	4.25	19.46	1.89	0.00
Na_2O	0.08	0.15	0.24	0.54	11.20	8.63	4.59	0.09	0.03	0.06	0.15	0.76	10.32	0.00
K_2O	0.00	0.00	0.00	0.00	0.44	1.21	6.37	0.00	0.00	0.00	0.00	0.00	0.44	0.00
Total	98.58	99.77	99.94	99.61	99.93	100.31	98.76	98.60	99.53	99.97	99.82	98.91	100.20	99.73

Ol, Opx, Pig, Aug, Ab, Anor, Or, and Chm are olivine, orthopyroxene, pigeonite, augite, albite, anorthoclase, intermediate alkali feldspar, and chromite, respectively.

Table 2. Representative chemical compositions of Fe-Ni metal and troilite in the Y-74359 and Y-74360 achondrites.

	Y-74359		Y-74360	
	Metal	Tr	Metal	Tr
S	0.00	36.65	0.02	37.09
Cr	0.04	0.00	0.02	0.00
Fe	92.97	63.15	95.71	62.89
Co	0.45	0.00	0.44	0.00
Ni	5.41	0.00	4.58	0.00
Total	98.87	99.80	100.77	99.98

Table 3. Bulk compositions (normalized to 100 wt %) of the Y-74360 achondrite and the K-rich and K-poor portions of the Y-74359 achondrite. Av. H is the average composition of the silicate portion of H chondrites (HARAMURA et al., 1983).

	Y-74359 K-rich		Y-74359 K-poor	Y-74360	Av. H
SiO_2	47.59		46.83	48.20	46.60
TiO_2	0.13		0.14	0.15	0.13
Al_2O_3	2.25		2.26	2.24	2.61
Cr_2O_3	0.97		0.83	0.92	0.60
FeO	14.34		15.44	14.36	15.31
MnO	0.42		0.42	0.43	0.37
MgO	31.31		31.26	30.92	31.03
CaO	1.64		1.67	1.81	2.30
Na_2O	0.64		1.00	0.86	0.95
K_2O	0.71		0.15	0.11	0.10
Total	100.00		100.00	100.00	100.00
Normative compositions					
Olivine	49.51	wt%	53.99	44.88	54.76
Fo	80.3	mol%	78.9	80.0	78.8
Fa	19.7		21.1	20.0	21.2
Pyroxene	37.88	wt%	33.98	43.62	32.86
Wo	7.1	mol%	7.9	6.2	10.5
En	74.5		72.7	75.1	70.4
Fs	18.4		19.4	18.7	19.1
Plagioclase	10.75	wt%	10.61	9.85	11.18
An	10.0	mol%	12.5	18.9	21.4
Ab	52.5		80.0	75.7	73.8
Or	37.5		7.5	5.4	4.8
Chromite	1.56	wt%	1.12	1.34	0.89
Ilmenite	0.30	wt%	0.30	0.30	0.30

and/or pyroxene grains. A chondrule-like substance is present (Fig. 1b), which consists of several barred olivine grains, up to 0.5 mm long, occurring in parallel. However, it is not clear whether the barred olivines are relics from a barred-olivine chondrule.

Olivine in Y-74360 has euhedral or subhedral outlines, and the size ranges from 10 to 100 microns across. It is sometimes included in large orthopyroxene grains.

Table 4. Major and trace element contents of the Y-74360 achondrite obtained by INAA.

	Y-74360		Average H chondrite*	
Fe	12.1	wt%	27.49	wt%
Mg	17.7		13.98	
Al	1.18		1.12	
Na	0.885		0.6232	
Cr	0.453		0.356	
Mn	0.332		0.24	
Ti	0.15		0.072	
Ni	0.076		1.72	
V	92.9	ppm	65	ppm
Co	82.0	ppm	900	ppm
Sc	10.4	ppm	7.4	ppm
Ir	19.7	ppb	750	ppb

* From PALME *et al.* (1981).

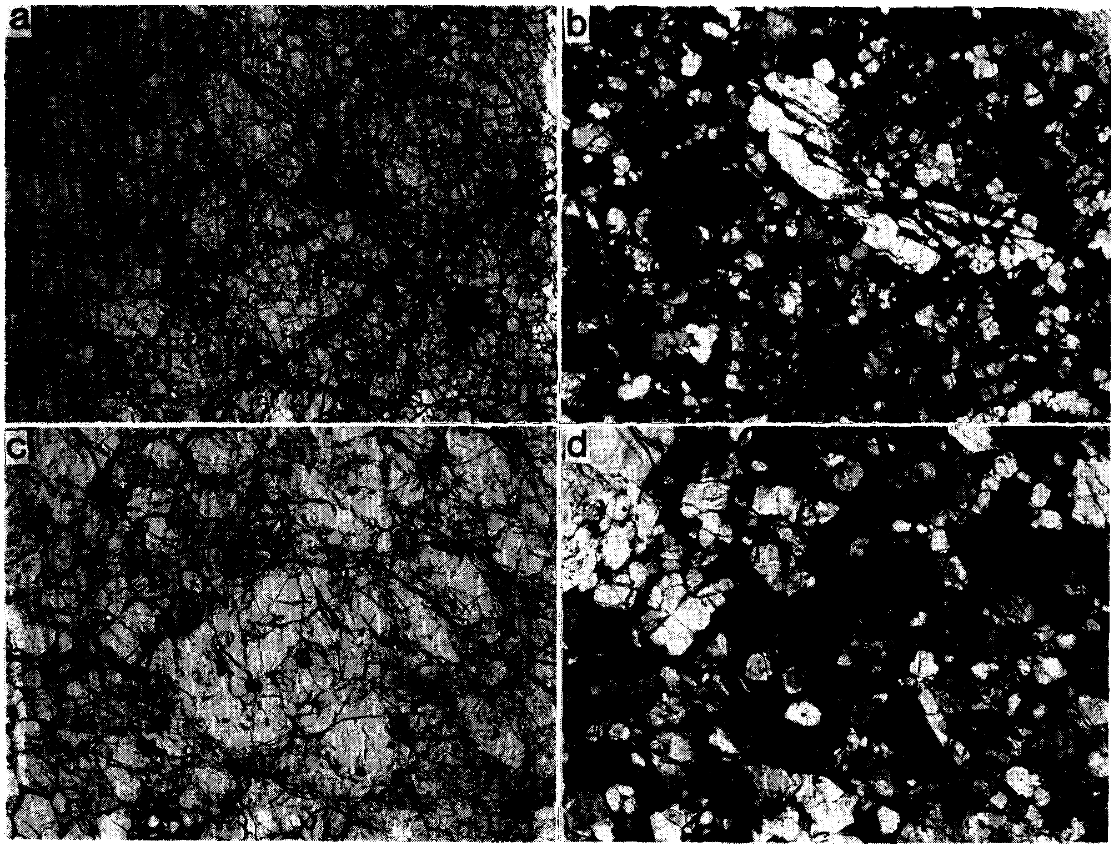

Fig. 1. Photomicrographs of Y-74359 (a: open polars, b: crossed polars) and Y-74360 (c: open polars, d: crossed polars). Transmitted light, and a width of 1 mm. Note that a chondrule-like substance occurs in the center of Fig. 1b and that small euhedral or subhedral olivine grains are included in larger orthopyroxene grains in Figs. 1b and 1d.

Orthopyroxene occurs as large euhedral grains, from 50 microns up to 1 mm in length, and low-Ca pyroxene, with polysynthetic twinning, is rarely included in large orthopyroxene grains. Several grains of chromite, Fe-Ni metal, and troilite, from 10 to 50 microns in size, are observed. Feldspar is cryptocrystalline and occurs in in-

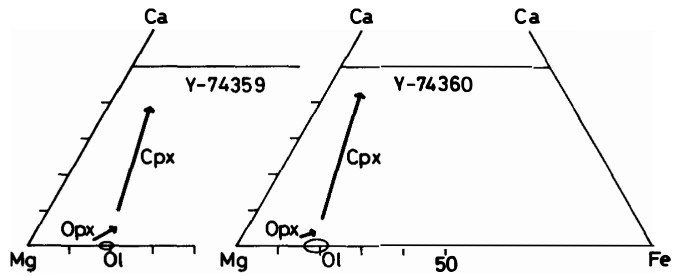

Fig. 2. Chemical compositions (in atomic %) of olivine (Ol), orthopyroxene (Opx), and clinopyroxene (Cpx) in Y-74359 and Y-74360. Olivines are plotted in the range shown by the small ellipses. Orthopyroxene shows slight, and clinopyroxene remarkable, compositional zoning as indicated by the arrows.

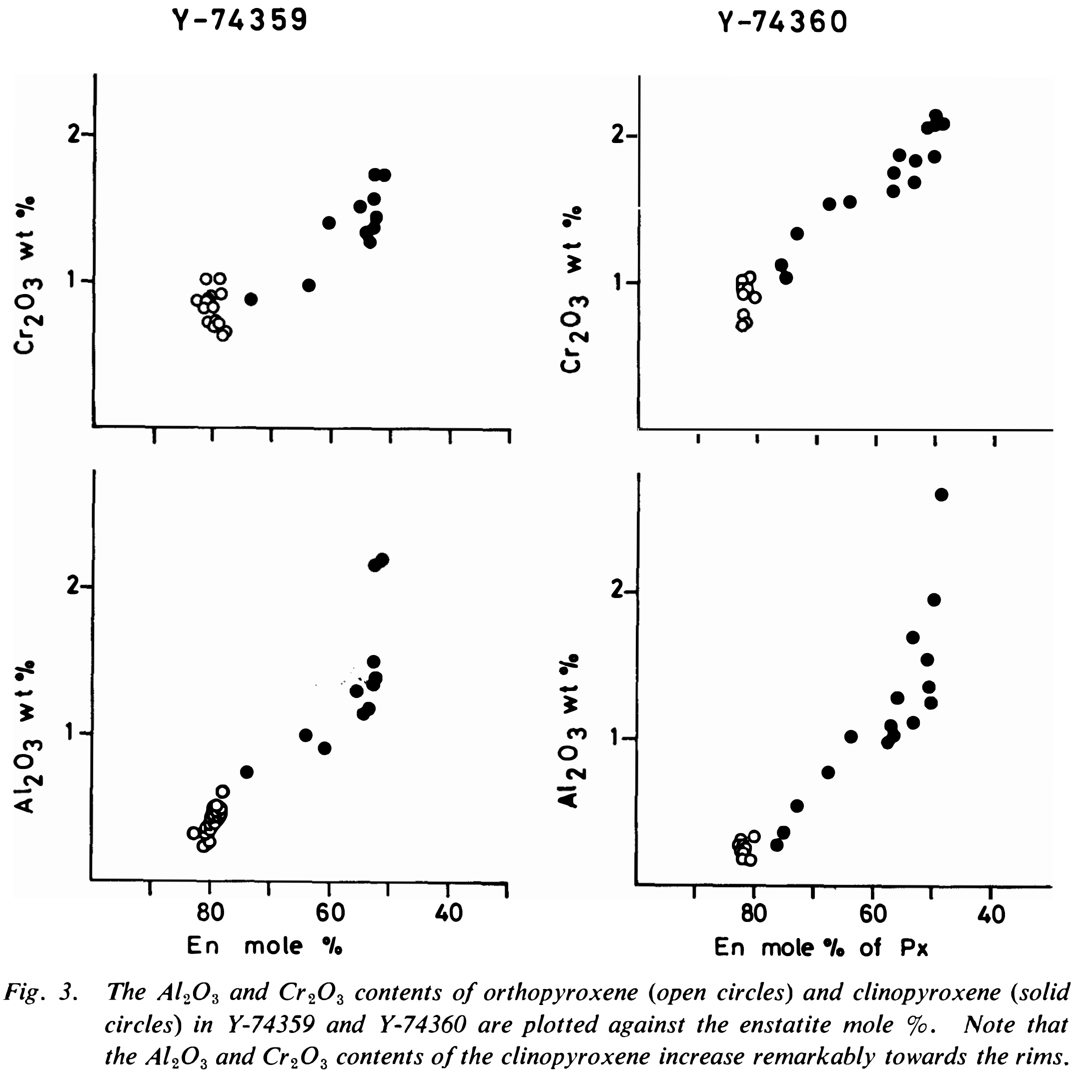

Fig. 3. The Al_2O_3 and Cr_2O_3 contents of orthopyroxene (open circles) and clinopyroxene (solid circles) in Y-74359 and Y-74360 are plotted against the enstatite mole %. Note that the Al_2O_3 and Cr_2O_3 contents of the clinopyroxene increase remarkably towards the rims.

terstitial spaces between olivine and/or pyroxene grains. Chondrule-like texture is not observed under the microscope.

Olivine in both the achondrites is homogeneous or has slight chemical zoning. The homogeneous olivine occurs as inclusions in orthpyroxene grains and is magnesian with the MgO/(MgO+FeO) mole ratios of about 0.82 to 0.83, and the olivine in contact with cryptocrystalline feldspar zones from magnesian cores to ferroan rims, and the MgO/(MgO+FeO) mole ratios range from 0.82 to 0.80 for Y-74359 and from 0.83 to 0.78 for Y-74360. The compositional ranges are shown in Fig. 2. Orthopyroxene is homogeneous at the cores of large grains, but small grains and rims of large orthpyroxene grains show slight chemical zoning, from Ca-poor magnesian

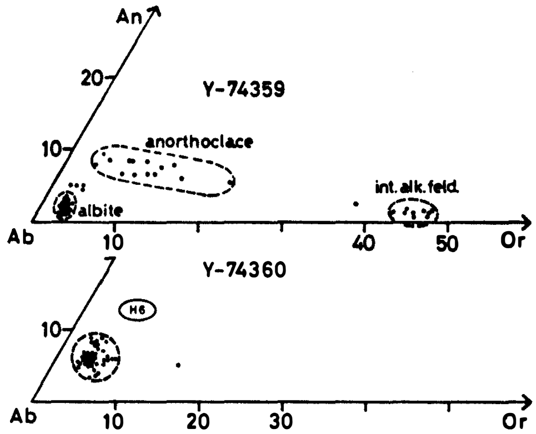

Fig. 4. Chemical compositions (in atomic % of Ca, Na, and K) of the cryptocrystalline feldspars in Y-74359 and Y-74360. The compositional range of plagioclases in equilibrated H chondrites (H6) is shown by a circle, for reference. Note that feldspars in Y-74359 are classified into three groups, albite, anorthoclase, and intermediate alkali feldspar, as shown by the dashed line circles, and that there are feldspars of intermediate composition between two of the groups in Y-74359, and an alkali feldspar rich in K occurs in Y-74360.

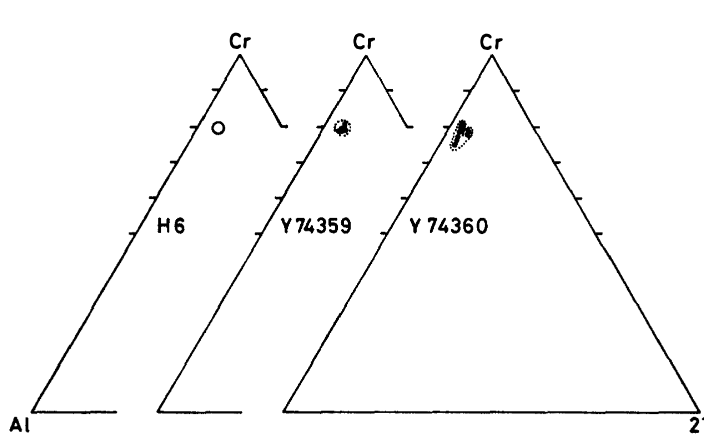

Fig. 5. Chemical compositions (in atomic %) of chromites in equilibrated H chondrites (H6), Y-74359 and Y-74360. Chromites in Y-74360 show slight compositional zoning, from Ti-poor cores to Ti-rich rims, via Al-rich chromites. Note that the chemical compositions of chromites in the both achondrites are similar to those in equilibrated H chondrites.

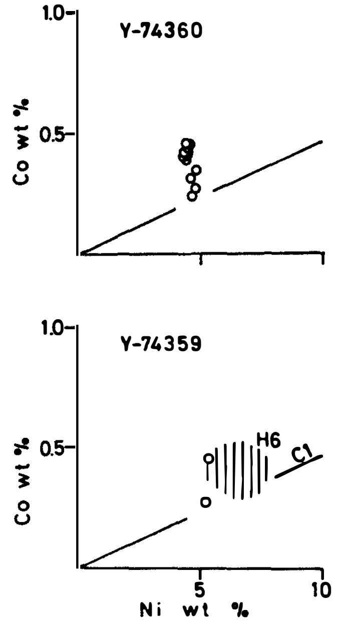

Fig. 6. The Co contents of Fe-Ni metals in Y-74359 and Y-74360 are plotted against their Ni contents. The hatched area represents the compositional range of Fe-Ni metal in equilibrated H chondrites (H6), and the straight line is the Co/Ni ratio of CI chondrites.

cores to Ca-rich ferroan rims, as shown in Fig. 2. On the other hand, clinopyroxene has remarkable chemical zoning continuously from pigeonitic cores to augitic rims (Fig. 2). The Al_2O_3 and Cr_2O_3 contents of the clinopyroxene increase from the pigeonitic core to the augitic rim (Fig. 3). Feldspar in Y-74360 is albite, and ranges from An_3 to An_9 (Fig. 4). Feldspars in Y-74359 are chemically classified into three groups, albite, anorthoclase, and intermediate alkali feldspar, and occur in different portions of Y-74359 (Fig. 4). Chromite in Y-74359 is homogeneous in chemical composition, but that in Y-74360 has slight chemical zoning, from Ti-poor cores to Ti-rich rims (Fig. 5). Fe-Ni metal in the both achondrites occurs in small amounts, and the Ni and Co contents are 4–6 wt% and 0.2–0.5 wt%, respectively (Fig. 6).

4. Discussion

4.1. Crystallization sequence of the Y-74359 and Y-74360 achondrites

The cryptocrystalline feldspar occurs in the interstitial spaces between euhedral pyroxene and olivine grains in both the achondrites, and the occurrence is similar to those of clean glasses in porphyritic olivine-pyroxene chondrules in unequilibrated ordinary chondrites. In addition to this, the pyroxenes in both the achondrites have chemical zoning similar to those in some kinds of porphyritic olivine-pyroxene chondrules (IKEDA, 1983). These suggest that the achondrites appear to have been produced from solid precursors by partial or batch melting, followed by relatively-rapid cooling which resulted in cryptocrystalline feldspars. Partial melting hypothesis for the achondrites is preferable for the following two reasons; first, cores of large orthopyroxene grains and olivine included in orthopyroxene grains are chemically homogeneous, suggesting that they were residues from the partial melting, and secondly, cryptocrystalline feldspars with different chemical compositions occur in Y-74359 (see the following Section 4.2), suggesting that Y-74359 has never experienced batch melting.

The crystallization sequence of the major minerals is schematically shown in Fig. 7. Olivine and most of the orthopyroxene exsisted previously, and then minor orthopyroxene and all clinopyroxene precipitated from a melt at the rims of the pre-existent orthopyroxene. Lastly, chromite and feldspar crystallized from the residual liquid in the interstitial spaces between the olivine and/or pyroxene grains. The clinopyroxene has remarkable compositional zoning in both the achondrites (Figs. 2 and 3), indicating that it crystallized rapidly in undercooling conditions similar to those of chondrules in unequilibrated chondrites. However, the absence of clean glass suggests that they crystallized more slowly than glass-bearing chondrules. Instead of glass, feldspar poorly crystallized in the interstitial spaces, resulting in cryptocrystalline feldspars.

The MnO contents of the mafic minerals are plotted against their FeO contents in Fig. 8. The MnO/FeO ratio of the orthopyroxene is slightly higher than that of the

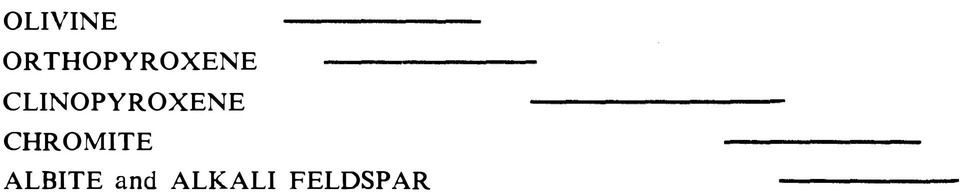

Fig. 7. Crystrallization sequence of Y-74359 and Y-74360.

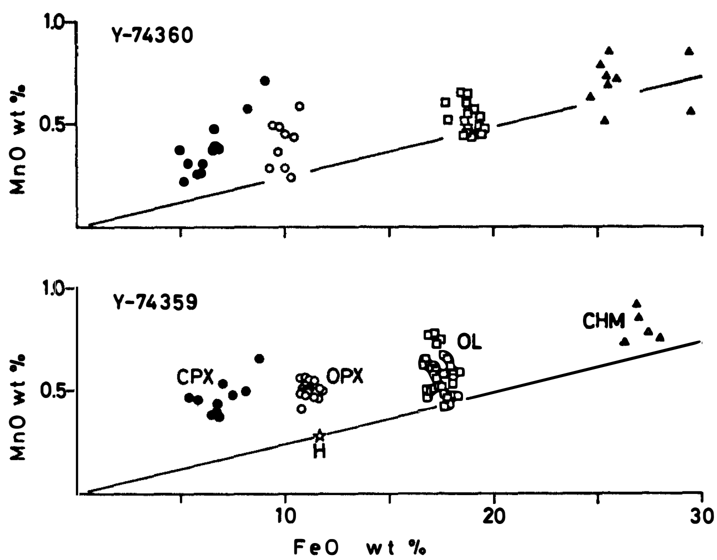

Fig. 8. The MnO contents of olivine (OL), orthopyroxene (OPX), clinopyroxene (CPX), and chromite (CHM) in Y-74359 and Y-74360, plotted against their FeO contents. Open star is the average of H chondrites (HARAMURA et al., 1983), and the MnO/FeO ratio is shown by the straight line.

olivine, indicating that these two phases are in equiliblium with one another. However, the FeO-richer clinopyroxene seems to be richer in MnO, resulting in its higher MnO/FeO ratio in comparison to the orthopyroxene. MnO/FeO ratio of clinopyroxene is nearly the same as that of orthopyroxene in eucritic meteorites (IKEDA and TAKEDA, 1985), and the high MnO/FeO ratio of the clinopyroxene in the achondrites may be due to its rapid crystallization.

The normative contents of feldspar and augite components of both the achondrites are about 15 wt% (Table 3), and as already stated in the above discussion, the cryptocrystalline feldspar and clinopyroxene crystallized from a melt. This suggests that the degree of partial melting must have been larger than about 15 wt%. Taking into account that all of the olivine and most of the orthopyroxene may be residues of the partial melting, the degree of partial melting might have been less than 30 wt%. The temperature of the partial melting should be higher than that of the melting point of albite, about 1120°C.

4.2. Heterogeneity of the Y-74359 achondrite

Three feldspar groups, albite, anorthoclase and intermediate alkali feldspar, are observed in Y-74359 (Fig. 4), and they occur heterogeneously in the thin section (Fig. 9). The intermediate alkali feldspars are observed in the K-rich portion, and the albites occur in the K-poor portion of Fig. 9. The anorthoclase is mainly observed in the border zone of the K-rich portion, from 100 to 200 microns in width, although it occurs sometimes within the K-rich and K-poor portions. Feldspars intermediate in composition between the intermediate alkali feldspar and anorthoclase, and between anorthoclase and albite (Fig. 4), are rarely observed on the boundaries of the respective areas of the three feldspar groups, less than a few tens microns in width. The occurrence of the three feldspar groups in Y-74359 suggests that the solid precursor of Y-74359 included chemically-different feldspars and that after partial melting crystallization took place so rapidly that it prevented the residual feldspathic melts from homogenizing.

On the other hand, feldspar in Y-74360 seems to have been homogenized during the partial melting event although one feldspar grain rich in K_2O was found (Fig.

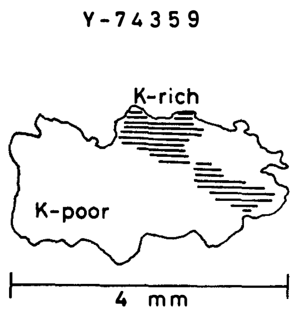

Fig. 9. A schematic map showing the K-rich and K-poor portions on a thin section of Y-74359. Intermediate alkali feldspar occurs in the K-rich portion denoted by the hatched area, and albite occurs in the K-poor portion denoted by the clear area. Anorthoclase is observed mainly in the border zone of the K-rich portion and rarely within the K-rich and K-poor portions.

4). The homogeneity of feldspar in Y-74360, in contrast with Y-74359, is consistent with the fact that the former is coarser-grained than the latter.

4.3. Similarities and differences between the both achondrites and equilibrated H chondrites

The major-element bulk chemical compositions of the Y-74359 and Y-74360 achondrites are generally similar to one another and to the average chemical composition of the silicate portion of H chondrites, except that the Ca and Al contents are slightly lower, and the Mn contents slightly higher, than those of the average H chondrite (Tables 3 and 4). The K content of K-rich portion (the hatched area of Fig. 9) of Y-74359 is decidely higher than that of the average H chondrite. Table 4 indicates that the Ni, Co and Ir contents of the two achondrites are depleted 10 to 40 times from that of the average H chondrite. The sulfide components are also depleted in the achondrites, because troilite occurs scarcely in the achondrites in contrast to the common occurrence in H chondrites.

The Mg/(Mg+Fe) ratios of olivine and orthopyroxene of the two achondrites are similar to those of the equilibrated H chondrite, and the chemical compositions of chromites are also similar (Fig. 5). However, the MnO contents of mafic minerals are slightly higher than those of the equilibrated H chondrite (Fig. 8). The Ni and Co contents of Fe-Ni metal in the two achondrites are similar to those of kamacites in the equilibrated H chondrite (Fig. 6), but taenites were not found in the achondrites. Plagioclase in the equilibrated H chondrites is oligoclase with an An content ranging from 10 to 20 mole %, and feldspars in the two achondrites are more sodic (Fig. 4).

The oxygen isotopic compositions of the Y-74359 and Y-74360 achondrites were reported by MAYEDA and CLAYTON (1989), concluding that the two achondrites are within the range of the equilibrated H chondrites.

4.4. Origin of the Y-74359 and Y-74360 achondrites

The two achondrites are similar to the equilibrated H chondrites in lithophile element contents and mineral compositions, but the siderophile and probably the chalcophile element contents are depleted. This suggests two hypotheses for the origin of the two achondrites. One hypothesis is that the achondrites were originally an H chondrite which lost its Fe-Ni metal and sulfide components during partial melting, and the other is that the achondrites were produced from a heterogeneous material originally depleted in metal and sulfide components prior to the partial melting, and the heterogeneous material was similar to the silicate portion of H chondrites in chemical and oxygen isotopic compositions.

The first hypothesis is as follows: Unequilibrated H chondrites were partially melted probably by shock events without homogenization of feldspathic components, and during the melting most of the Fe-Ni metal and Fe sulfide components was lost. Olivine, and most of orthopyroxene, remained unmelted and homogenized, but the silicate melt was chemically heterogeneous. The melt rapidly crystallized minor orthopyroxene and later clinopyroxene, producing the remarkable chemical zoning of the clinopyroxene. The rapid crystallization, without homogenization of feldspathic components, resulted in heterogeneous residual melt pockets which differed in feldspathic composition in different portions of the meteorite. Finally cryptocrystalline feldspar crystallized interstitially in the different portions of these meteorites (Fig. 10).

The second hypothesis is as follows: Rapid condensation in the protosolar nebula produced a heterogeneous silicate material which included chemically-different feldspar grains. This heterogeneous material was the precursors of chondrules of unequilibrated H chondrites, and the precursors were depleted in Fe-Ni metal and sulfide components. They were melted without thorough homogenization to produce silicate-melt droplets and large partially-melted masses (or "enormous chondrule

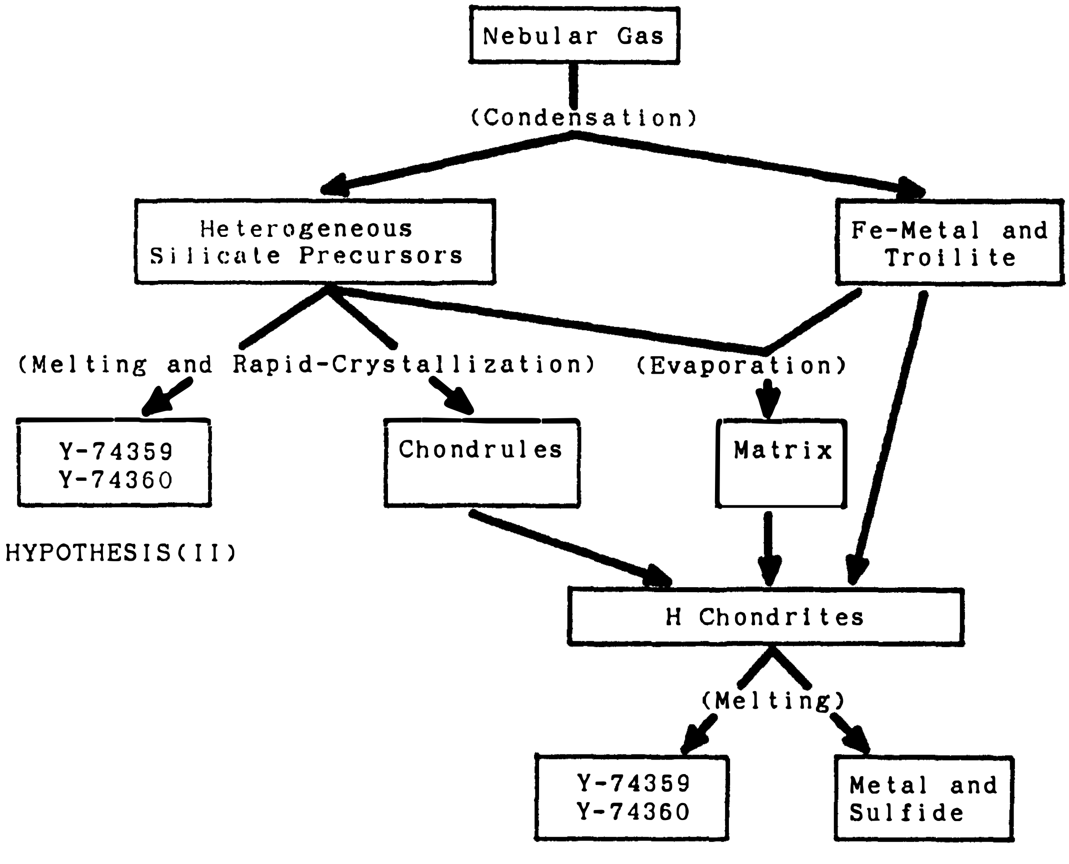

Fig. 10. The two hypotheses for origin of the Y-74359 and Y-74360 achondrites are schematically shown. Hypothesis (I) is that unequilibrated H chondrites were partially melted, and Fe-Ni metal and sulfide components were lost during the partial melting, resulting in the two achondrites. Hypothesis (II) is follows; Condensation took place in a nebular gas, and heterogeneous silicates precursors which already depleted in Fe-Ni metal and sulfide components were produced. They were precursors of chondrules in H chondrites. Flash-melting took place probably by shock events and produced chondrule melt droplets and partially-melted blocks from the heterogeneous silicate precursors. The chondrule melt droplets and partially-melted blocks cooled rapidly to result in normal chondrules and the Y-74359 and Y-74360 achondrites, respectively. The normal chondrules accreted on the H chondrite parent body with Fe-Ni metal and sulfide components and the matrix component to produce H chondrites.

melts"), which crystallized rapidly, resulting in normal chondrules and the two achondrites, respectively (Fig. 10). The existence of a chondrule-like substance in Y-74359 (Fig. 1b) is not a problem for the hypothesis, because formational processes of chondrules may have been repeated prior to the final chondrule formation.

The second hypothesis seems to be preferable to the first one, for the following reasons. According to the first hypothesis, most of the Fe-Ni metal and sulfide components should be lost during the partial melting event, without thorough homogenization of the alkalis in this melt. However, olivine and pyroxene grains in Y-74359 are fine-grained, suggesting that the duration of the partial melting event was relatively short, so as to prevent the coarsening of olivine and pyroxene during the partial melting. In addition to this, the cryptocrystalline feldspar in Y-74359 and Y-74360 indicates that after the partial melting event the meteorites cooled rapidly enough to prevent the crystallization of coarse-grained feldspar. These evidences suggest that the achondrites were heated probably by shock events and cooled in a short time span to prevent the loss of metal and sulfide components, just as holocrystalline chondrules in unequilibrated ordinary chondrites (IKEDA, 1980).

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