OXYGEN ISOTOPIC COMPOSITIONS OF PETROGRAPHICALLY DESCRIBED INCLUSIONS FROM ANTARCTIC UNEQUILIBRATED ORDINARY CHONDRITES

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Abstract: Several inclusions from the Antarctic unequilibrated ordinary chondrites (ALH-764(LL3), ALH-77015(L3) and Y-790448(L3)) were excavated and their petrography, chemical and oxygen isotopic compositions were determined. The coherent data indicates that precursors of the ordinary chondrites consist of a mixture of two different solid materials. One is a pre-existing solid enriched in albite component and depleted in ^{16}O component and the other is a solid depleted in albite component and enriched in ^{16}O component. The latter solid material may be an evaporation residue of the former solid material in an ambient gas.

1. Introduction

MAYEDA *et al.* (1980) discovered a new ^{16}O mixing line defined by oxygen isotopic compositions of several inclusions in an unequilibrated ordinary chondrite (UOC), ALHA76004(LL3) meteorite. The new mixing line is quite different from the carbonaceous chondrite mixing line (CLAYTON *et al.*, 1977), being displaced towards higher $^{17}O/^{16}O$ by 3‰ on the oxygen three isotope diagram. The new line coincides with the best-fit line determined by the data of individual chondrules from ordinary chondrites (GOODING *et al.*, 1980). We consider, therefore, that the new line holds the key to understand the origin of precursors of ordinary chondrites in the proto-solar nebula.

The purpose of this study is to confirm whether the new line is supported by inclusions from other UOC meteorites or not, and to get coherent data on petrography, chemical and isotopic compositions of the inclusions. We have cut out five inclusions from three different Antarctic UOC meteorites (two in ALH-764 (LL3) which is equivalent to ALHA76004, one in ALH-77015(L3) and two in Y-790448(L3)). One half of each specimen was used for petrographic description and determination of major chemistry. The other half was for determination of oxygen isotopic composition. In this paper, we present petrographic, chemical and isotopic data of these inclusions and discuss the relationship between their chemical and isotopic compositions.

2. Petrographic Description of the Inclusions and Chondrules

The brief petrography of the inclusions and chondrules is as follows.

2.1. *ALH-77015A*

ALH-77015 is an L3 chondrite, consisting of a massive aggregate mainly of chondrules and lithic inclusions with interstitial matrix. The sample ALH-77015A (Figs. 1a and 1b) is a lithic inclusion or a fragment of larger chondrule, consisting mainly of large olivine crystals and low-Ca clinopyroxenes surronding the large olivine crystals. Groundmass (or mesostasis) is observed in the spaces surrounded by low-Ca pyroxene crystals. Orthopyroxenes are included within the large olivine crystals, showing corroded form (Fig. 1b). Chemical compositions of orthopyroxene, low-Ca pyroxene and groundmass are shown in Table 1. Small glass inclusions less than about 10 microns across are observed in the large olivine crystals. Their chemical compositions are also tabulated in Table 1, and they vary remarkably in chemical composition among the

Table 1. Representative chemical campositions of the constituent minerals and groundmass in ALH-77015, ALH-764 and Y-790448. Opx, Cpx, Gm, Inc, Pl and Px are orthopyroxene, clinopyroxene, groundmass, glass inclusions, plagioclase and pyroxene, respectively.

	ALH-77015A									
	Opx	Opx	Cpx	Cpx	Cpx	Gm	Inc	Inc	Inc	Inc
Na_2O	0.04	0.00	0.03	0.01	0.49	8.63	2.82	1.32	3.45	0.20
MgO	30.35	33.04	21.47	28.75	13.21	2.32	2.04	1.76	0.02	0.46
Al_2O_3	0.17	0.54	0.73	0.24	4.51	18.62	13.27	11.33	12.14	2.02
SiO_2	56.17	55.62	52.00	55.10	48.02	50.18	74.51	76.09	78.42	94.98
K_2O	0.00	0.00	0.00	0.00	0.00	0.21	0.01	0.22	6.17	0.01
CaO	0.30	0.32	1.74	0.48	13.64	8.20	7.25	6.87	0.04	1.17
Cr_2O_3	0.44	0.50	0.46	0.54	0.18	0.05	0.00	0.25	0.12	0.00
MnO	0.19	0.27	0.29	0.33	0.25	0.40	0.10	0.00	0.11	0.07
FeO	12.17	9.58	22.93	15.52	18.19	11.79	1.50	1.48	0.60	0.50
Total	99.84	99.88	99.64	100.98	98.50	100.40	101.51	99.31	101.06	99.42

	ALH-764B						Y-790448A			Y-790448B	
	Gm	Gm	Cpx	Cpx	Cpx	Pl	Pl	Px	Px	Px	Px
Na_2O	5.00	1.04	0.06	0.04	0.74	1.25	1.35	0.01	0.00	0.02	0.02
MgO	15.49	3.14	34.74	36.38	18.10	0.47	0.63	31.51	34.40	29.36	32.46
Al_2O_3	3.77	15.61	0.39	0.45	1.70	33.67	33.47	2.88	0.74	1.83	1.33
SiO_2	54.38	71.54	56.98	55.84	51.70	45.10	45.24	54.25	56.76	54.88	56.73
K_2O	1.73	1.77	0.02	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00
CaO	8.52	2.73	1.28	0.44	17.09	18.49	18.82	2.40	1.40	2.14	1.82
Cr_2O_3	1.33	0.05	0.93	0.77	1.94	0.01	0.03	0.97	0.46	0.78	0.62
MnO	0.19	0.11	0.57	0.42	0.50	0.00	0.05	0.22	0.25	0.18	0.12
FeO	4.55	1.45	5.18	4.82	5.29	0.90	0.87	7.33	6.87	10.99	6.51
Total	94.94	97.45	100.16	99.17	97.28	99.89	100.47	99.58	100.89	100.18	99.60

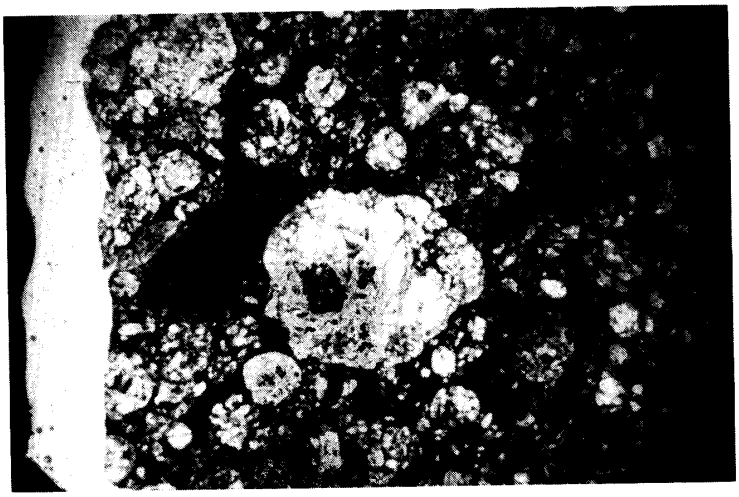

Fig. 1a. ALH-77015A is central white inclusion. Long dimension is about 9 mm.

Fig. 1b. ALH-77015A. Crossed polars. Large black square part (central to left) is a relic olivine crystal including elongating corroded orthopyroxenes (whitish rods). Right part is an aggregate of pyroxene crystals which crystallized from a melt surrounding the relic large olivine. Long dimension is about 3 mm.

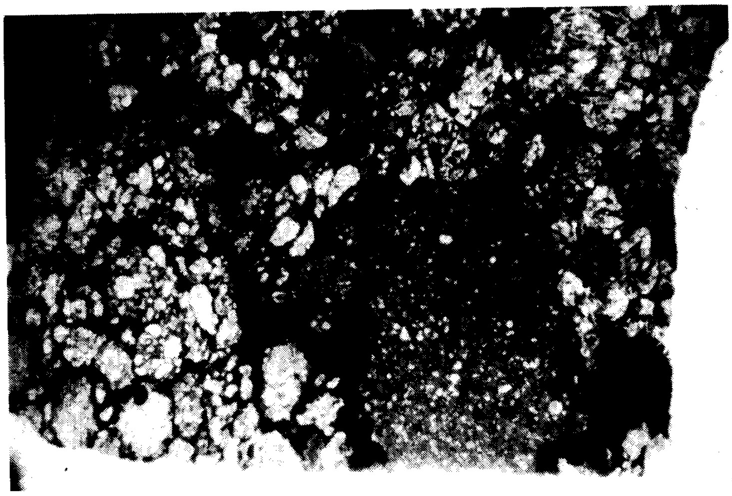

Fig. 1c. ALH-764B (lower right) is the largest inclusion in this view. Long dimension is about 9 mm.

Fig. 1. Photographs of the samples.

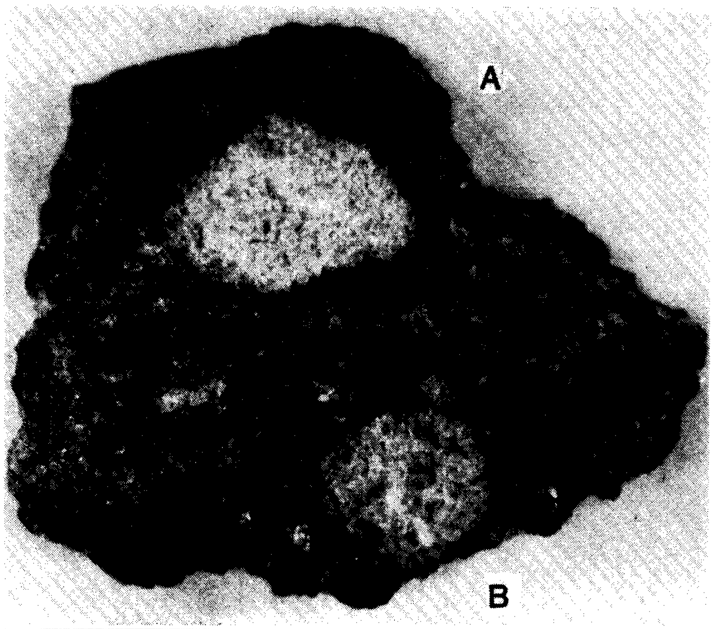

Fig. 1d. Y-790448A (upper white inclusion) and Y-790448B (lower white inclusion). Longest axis of the chip is about 15 mm.

Fig. 1e. Y-790448A is an irregular aggregate of pyroxene crystals including many small olivine grains. White zone of lower part was eroded during the sample preparation. Long dimension is about 3 mm.

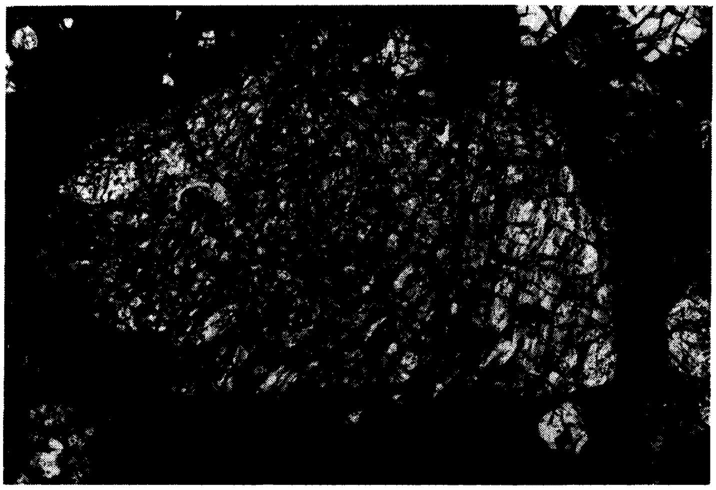

Fig. 1f. Y-790448B. Long dimension is about 3 mm.

Fig. 1. Photographs of the samples.

glass inclusions, indicating their non-equilibrium occurrence. The large olivine crystals including glass inclusions and corroded orthopyroxenes may be relic minerals, whereas low-Ca clinopyroxenes crystallized from the silicate melt surrounding the large relic olivine crystals. The compositional ranges of main constituent minerals are as follows.

Ol: $Fo_{82-85}Fa_{18-15}$
Opx: $Wo_{0.5-1.5}En_{81-86}Fs_{13-18}$
low-Ca Cpx: $Wo_{1-5}En_{60-76}Fs_{23-36}$
high-Ca Cpx: $Wo_{30}En_{40}Fs_{30}$

2.2. *ALH-764A*

ALH-764 is an LL3 chondrite which is a massive aggregate of chondrules, lithic inclusions and mineral fragments with interstitial matrix. The sample ALH-764A is a holocrystalline chondrule including a large olivine crystal and corresponds to "No. 300" chondrule in IKEDA (1980) where a brief description is given.

Ol: $Fo_{90-78}Fa_{10-22}$
Cpx: $Wo_{8-16}En_{71-79}Fs_{10-13}$
Pl: $An_{79-83}Ab_{17-20}Or_{0.5}$

2.3. *ALH-764B*

The sample (Fig. 1c) is a fine-grained lithic inclusion consisting of a fine- to medium-grained olivine and pyroxene aggregate with interstitial groundmass materials. Small amounts of Fe-Ni metal and troilite occur. Olivines are euhedral to subhedral and usually 10 to 30 microns in size, the largest being up to 200 microns. Large olivine crystals show chemical zoning from CaO-rich magnesian core to CaO-poor ferrous rim. Low-Ca clinopyroxene grains are euhedral and smaller than about 130 microns. Small high-Ca clinopyroxene grains occur with the interstitial groundmass.

Ol: $La_{1.0-0.0}Fo_{98.5-86}Fa_{0.5-14}$
low-Ca Cpx: $Wo_{0.5-2.5}En_{93-90}Fs_{6-8}$
high-Ca Cpx: $Wo_{37}En_{54}Fs_{9}$

2.4. *Y-790448A*

Y-790448 is an L3 chondrite, consisting of chondrules, lithic inclusions and mineral fragments with the interstitial matrix. The sample Y-790448A (Figs. 1d and 1e) is a lithic inclusion consisting of an olivine and orthopyroxene aggregate with small amounts of plagioclase. Olivines are round grains included in large pyroxene crsytals, showing poikilitic texture. The chemical compositions of the constituent minerals (Table 1) are fairly uniform and may have suffered intense recrystallization.

Ol: $Fo_{84-88}Fa_{12-16}$
Px: $Wo_{2-5}En_{84-88}Fs_{9-11}$
Pl: $An_{88-93}Ab_{7-12}$

2.5. *Y-790448B*

The sample (Fig. 1f) consists of barred olivine and pyroxene with very fine-grained plagioclase. The width of the olivine bars is about 10 microns. This may be a recrystallized chondrule which had shown barred-olivene texture. Chemical compositions of pyroxene are shown in Table 1.

Ol: $Fo_{75-78}Fa_{22-25}$
Px: $Wo_{2.5-4}En_{79-87}Fs_{10-16.5}$

3. Results and Discussion

Oxygen isotopic compositions of the bulk meteorites and the inclusions or chondrules were determined by an improved method (Clayton and Mayeda, 1983). Bulk chemical analyses of the inclusions or chondrules were obtained using a defocussed beam of an electron-probe microanalyzer with a correction method for polyphases (Ikeda, 1980). The results are shown in Tables 2 and 3, respectively.

Table 2. Oxygen isotopic compositions of the whole rocks (WR) and the inclusions (or chondrules).

	$\delta^{17}O$ (‰)	$\delta^{18}O$ (‰)
ALH-77015 (WR)	+3.22	+4.13
ALH-77015A	+2.60	+3.97
ALH-764 (WR)	+4.11	+5.55
ALH-764A	+2.95	+4.60
ALH-764B	+3.68	+5.14
Y-790448 (WR)	+3.30	+4.55
Y-790448A	+2.80	+4.48
Y-790448B	+2.07	+3.33

Table 3. Chemical compositions of the inclusions and chondrules.

	Y-790448A	Y-790448B	ALH-764A	ALH-764B	ALH-77015A
Na_2O	0.11	0.04	0.26	1.54	0.05
MgO	32.61	31.03	40.45	32.26	33.00
Al_2O_3	3.46	1.34	3.30	3.25	0.40
SiO_2	43.25	45.55	41.30	48.19	42.53
K_2O	0.03	0.02	0.06	0.51	0.02
CaO	3.08	1.70	3.15	2.08	0.61
TiO_2	—	—	—	—	—
Cr_2O_3	0.87	0.80	0.83	0.99	0.67
MnO	0.17	0.19	—	0.44	0.24
FeO	9.25	10.59	9.33	8.98	18.21
Total	92.83	91.26	98.68	98.24	95.64

Oxygen isotopic compositions of whole rocks and their inclusions or chondrules of the three UOC's, ALH-77015, ALH-764 and Y-790448, are plotted in Fig. 2. A line drawn in the figure is the new mixing line reported by Mayeda *et al.* (1980). Of three whole rock analyses obtained in this work, ALH-764 (WR) falls on the mixing line defined by the same meteorite, and Y-790448 (WR) falls near the line and within L6 region, while ALH-77015 (WR) is displaced from the line and is located between the

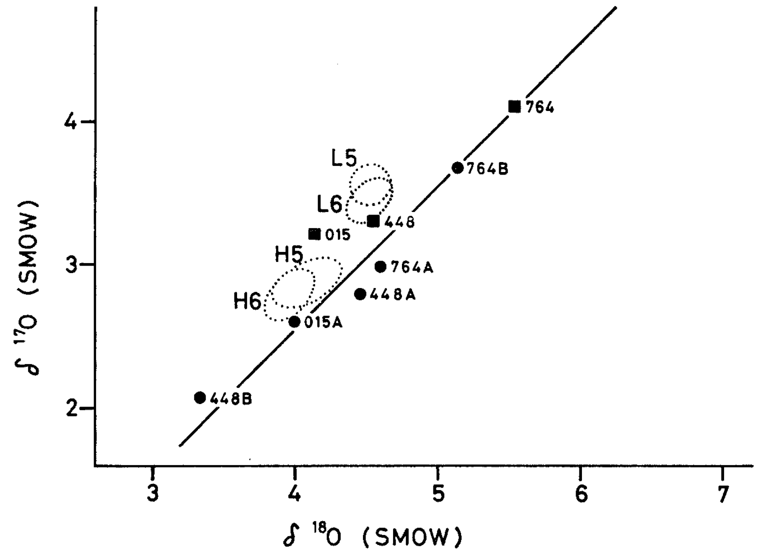

Fig. 2. Three oxygen isotope plotting in ‰. Solid squares are whole rock data of ALH-764 (764), Y-790448 (448) and ALH-77015 (015). Solid circles are inclusions or chondrules. Dodded regions are the compositional ranges of whole rocks of equilibrated ordinary chondrites (H5, H6, L5 and L6). Solid line is the mixing line of ALH-764 (MAYEDA et al., 1980).

two EOC (equilibrated ordinary chondrite) regions. The displacement is considered to be due to the terrestrial weathering in Antractic ice. According to the Antarctic Meteorite Newsletter (Vol. 4(1), 1981), the degrees of weathering of ALH-764 and ALH-77015 are A (minor) and C (severe), respectively. That of Y-790448 seems to be A/B (moderate).

Five inclusions (or chondrules) from the three UOC's fall on or near the mixing line as shown in Fig. 2. This is evidence that the mixing line defined by a UOC (ALH-764) holds on another two UOC's (ALH-77015 and Y-790448). ALH-764 shows the largest variation in ^{16}O components among them.

It should be noted that whole rock data of four groups (H5&6, L5&6) from equilibrated ordinary chondrites do not fall on the new mixing line. The displacement may imply that thermal metamorphism did operate in UOC in an open-system rather than in a closed-system, or components of UOC were originally different from those of EOC.

Figure 2 also shows that all inclusions or chondrules are enriched in ^{16}O components, when compared with their bulk components. In other words, there exist some unknown ^{16}O-poor components in these UOC's. A plausible candidate is "alkali-rich glass" in inclusions or chondrules. MAYEDA *et al.* (1980) had clarified, employing a low-temperature fluorination technique, that oxygen isotopic composition of an alkali-rich glass component in a dunitic inclusion of ALH-764 shows more depletion in ^{16}O component than those of the bulk inclusion.

CLAYTON (1981) suggested that the mixing took place by oxygen isotopic exchange mechanism between a gas and a pre-existing solid. The heavy component was the

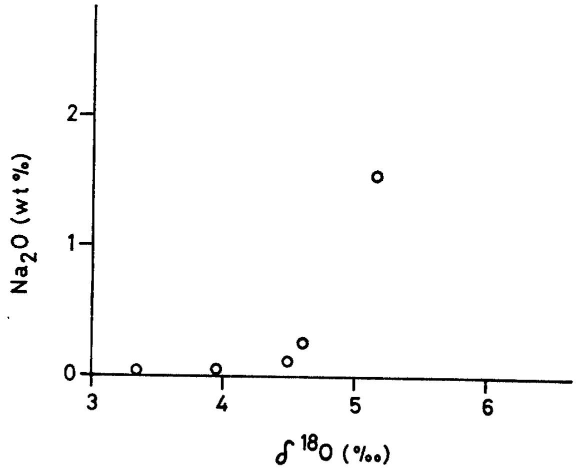

Fig. 3. Na_2O contents of five inclusions or chondrules, ALH-77015A, ALH-764A and B, and Y-790448A and B are plotted against their ^{18}O values.

gas and the light component was the solid, since in the dunitic inclusion consisting of olivine and glass, the glass has 4‰ greater $\delta^{18}O$ and $\delta^{17}O$ than the olivine. The glass is more easily exchanged with the gas.

Generally speaking, there are three possibilities for the endmembers of the mixing line. One is a gas-solid system in which the initial solids are ^{16}O-rich relative to the ambient gas with which it exchanges. CLAYTON (1981) has chosen this possibility by analogy with the interpretation of the mixing line for carbonaceous chondrites.

The second possibility is a solid-solid system with different isotopic compositions. A melt (or glass) composed of a mixture of the two different solids in vacua (or at instantaneous heating in an ambient gas) makes the mixing line. In this case, we could expect a correlation between oxygen isotopic composition and chemical composition. In Fig. 3, Na_2O contents of the inclusions and chondrules are plotted against their $\delta^{18}O$ values. As can be seen in the figure, there is a positive correlation. Na_2O contents in inclusions or chondrules form the normative albite component. Therefore, it cannot be ruled out that the endmembers of the mixing line are two different solid materials. One is a pre-existing solid which is enriched in albite component and depleted in ^{16}O component and the other is a pre-existing solid which is depleted in albite component and enriched in ^{16}O component. It is interesting to note that ALH-77015A and ALH-764B contain chemically heterogeneous glass inclusions in olivines or groundmass, as shown in Table 1. This fact suggests that the pre-existing solid or the precursor of the inclusions or chondrules was aggregates of non-equilibrium mineral assemblages.

A third possibility is a gas-solid exchange in the direction opposite to that proposed by CLAYTON (1981), as was discussed by CLAYTON *et al.* (1983). In this case, the correlation of oxygen isotopic composition with sodium content might result from vaporization loss of sodium in these inclusions or chondrules that were most strongly heated.

At present, the data are too few to make a firm assignment for the mixing mechanism, or for specification of the chemical and isotopic compositions of the endmembers of the mixing line.

Acknowledgments

This research was supported by National Science Foundation grant EAR 78-23680 and NASA grant NGL-14-001-169.

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(Received June 16, 1983; Revised manuscript received August 19, 1983)