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TERRESTRIAL ALTERATION OF Fe-Ni METALS IN ANTARCTIC ORDINARY CHONDRITES AND THE RELATIONSHIP TO THEIR TERRESTRIAL AGES

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Abstract: Terrestrial alteration of Fe-Ni metals to limonites in ordinary chondrites is faster for kamacite than for taenite. H chondrites which have high ratios of kamacite/taenite alter more easily than LL chondrites which have the low ratios, L chondrites being intermediate. Qualitative weathering indices, A, B, and C, correspond to measured average alteration degrees (proportion of metal converted to limonite) of $<5\%$, 10-20%, and $>50\%$, respectively. The surfaces of chondritic meteorites show higher degrees in alteration of Fe-Ni metals than the interiors, although the difference in the degree is merely a factor of two. There is no correlation between the average alteration degrees and the terrestrial ages for H and L chondrites, but the average alteration degree seem to depend upon the degrees of impact shocks which the chondrites had suffered in or on the parent body.

1. Introduction

Antarctic meteorites have more or less suffered terrestrial alteration in or on Antarctic ice since their fall on the Earth. Fe-Ni metals in Antarctic ordinary chondrites have often changed to alteration products and seem to have altered more easily than the coexisting silicates, oxides and sulfides.

Weathering index is qualitatively defined to indicate the degrees of terrestrial alteration for Fe-Ni metals in chondrites: A for minor rustiness, B for moderate, and C for intense rustiness. However, the definition of the weathering index is vague, and the physical meaning is not clear (GOODING, 1989). In addition to these, the comparison of the weathering index between laboratories is very difficult because the criteria for the definition largely depend on the personality.

We measured quantitatively the alteration degrees of Fe-Ni metals in Antarctic ordinary chondrites and will discuss the following problems: (1) What is the relationship between the alteration degree and weathering index? (2) Do kamacite and taenite suffer the terrestrial alteration to the same degree? (3) How does the alteration degree very from surface to interior in a meteorite? and (4) Is there any relationship between the alteration degree and the terrestrial age?

2. Analytical Methods and Samples

We measured the alteration degree of a Fe-Ni metal grain in chondrites under the microscope. Figure 1 shows an example of measurement of alteration degree; a large Fe-Ni metal grain is divided into four parts of equal-area using the cross-hairs under the microscope, and the quarter part is further divided into two or four parts with the eye. The area of alteration products (limonite) is estimated with the eye by comparison with the divided area under the microscope. Sometimes the alteration products occur in several peripheral portions of a Fe-Ni metal grain, and the total areal percentage is given by the summation of each area of the alteration products. The total areal percentage is defined to be "alteration degree" of the Fe-Ni metal grain.

Ordinary chondrites include many Fe-Ni metal grains which range in size from several mm across to smaller than a micron. We measured metal grains larger than 50–100 microns across in a chondrite. The alteration degrees of Fe-Ni metal grains in a chondrite are averaged to define "average alteration degree" for the chondrite. In order to estimate the error in the average alteration degree, we measured the average alteration degrees for three different portions in a thin section of Y-7301 (H5): the numbers of metal grains measured for each portion are 24, 59, and 74, respectively, and the average alteration degrees are 61, 63, and 67%, respectively. For this case, the average alteration degree for the chondrite is 64% with an error of 3%.

Unequilibrated chondrites sometimes have very fine-grained porous matrices which fill the interstitial spaces among chondrules and mineral fragments. On the other hand, equilibrated chondrites consist of well-recrystallized minerals, resulting in compact and homogeneous meteorites. Therefore, equilibrated chondrites are preferable to unequilibrated ones when comparing the alteration degrees with each other. The samples studied are 13 equilibrated L and H chondrites and one unequilibrated L chondrite (Table 1).

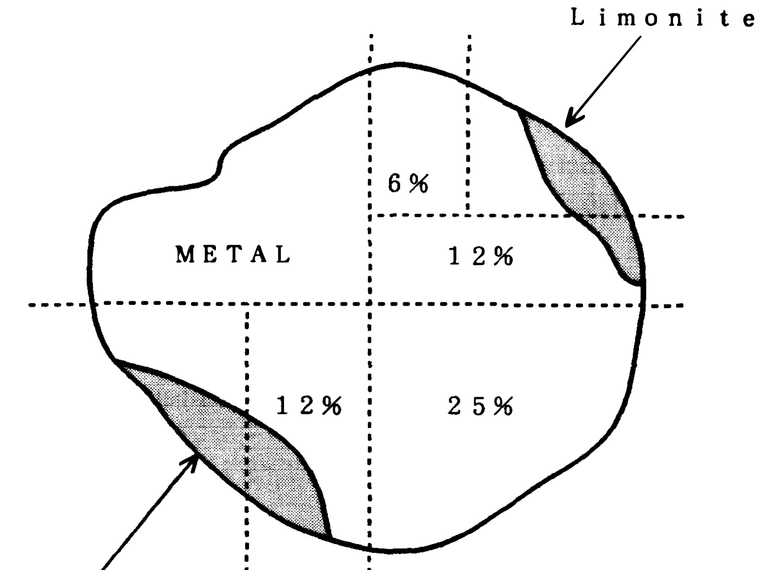

Fig. 1. Estimation of alteration degree of a Fe-Ni metal grain. The grain is divided into four parts of equal area by cross hairs under a microscope. A quarter is further divided with the eye into two (12%) or four (6%) parts. By comparison with the small areas, areal percentage of alteration products (limonite) is obtained.

Table 1. Average alteration degrees of chondrites.

		Weathering index[1]	Dist. from surf[2]	No. of grain[3]	Average alteration degree	Histo-gram[4]	Terrestrial age (10^3 y)[5]
Y-7301	H5			157	64	bi	90 ±100
Y-7304	L6		0–1 cm	38	12	uni	7 ± 1
Y-7305	L6			107	22	bi	<60[6]
Y-74155	H4	A		68	2.2	uni	
Y-74156	H4	A	0–1 cm	106	1.8	uni	55 ± 55
			1–2 cm	104	1.0	uni	
			2–3 cm	85	1.7	uni	
Y-74459	H6	C		32	51	bi	22 ± 2
Y-75102	L6			44	11	bi	3 ± 1
MBR-761	H6	B		85	18	bi	>39
ALH-761	L6	A	0–1 cm	114	15	bi	
			5 cm	122	12	bi	
			8 cm	57	8	bi	
ALH-768	H6	B/C		99	33	bi	100 ± 70
ALH-77002	L5	B	0–1 cm	20	55	bi	820 ± 80
ALH-77214	L3	C		41	57	bi	120 ± 80
ALH-77231	L6	A/B	5 mm	53	11	bi	600 ± 70
			10 mm	61	10	bi	
			17 mm	59	5	bi	
			27 mm	33	6	bi	
ALH-77272	L6	B/C		35	15	bi	530 ± 80

[1]YANAI and KOJIMA (1987); [2]Distance from the surface of the meteorites into the interior; [3]Numbers of measured metal grains; [4]uni and bi: unimodal and bimodal distributions; [5]NISHIIZUMI *et al.* (1989); [6]TAKAOKA (1987).

3. Histogram of Alteration Degrees

Histograms of alteration degrees of Fe-Ni metal grains for each chondrite are shown in Figs. 2 and 3. Most chondrites show bimodal distribution of alteration degrees of Fe-Ni metals in the histograms, although a few chondrites show unimodal distribution. The bimodal distribution comprises two remarkable peaks; one consists mainly of slightly-altered metal grains and the other includes intensely-altered grains showing more than 90% alteration degrees.

Figure 4 shows distribution of Fe-Ni metal grains larger than a few tens of microns across in a thin section of the ALH-77231 chondrite (L6). The intensely-altered metal grains occur in two small areas about 1 mm across where metal grains with alteration degrees more than 90% are observed. Moderately-altered grains (alteration degrees less than 20%) occur in several small areas about 1 mm across, and slightly-altered grains (alteration degrees less than 5%) occur outside the intensely- and moderately-altered areas. It is the localization of altered metal grains that results in bimodal distribution of the alteration degrees in the histograms. We do not know the exact reason why the localization took place, but it is possible that impact shocks caused the localization; when a chondrite suffered impact shocks in or on the parent body, the stress due to the shocks concentrated in small areas about 1 mm across, and

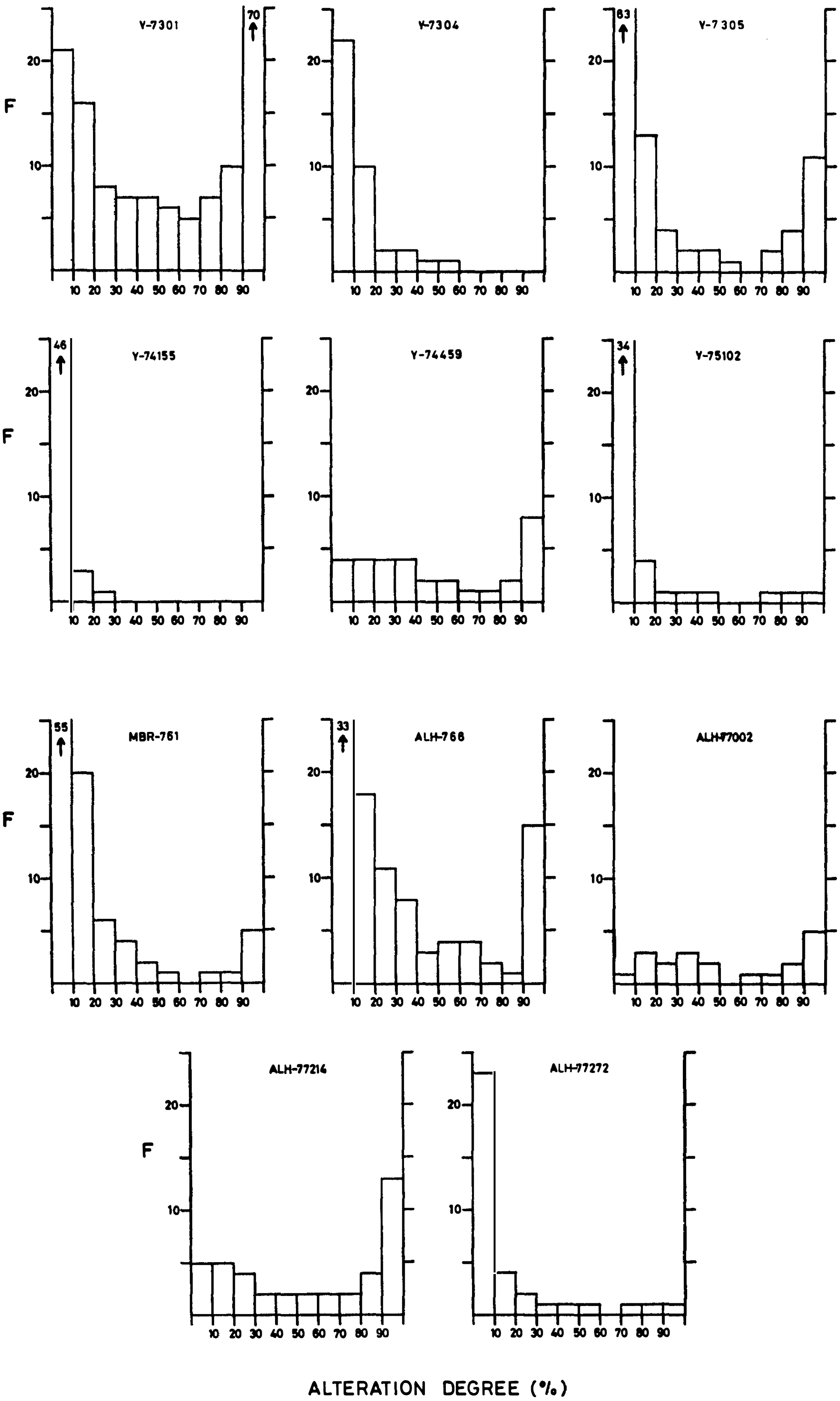

Fig. 2. Histograms showing frequency (F) of alteration degrees of Fe-Ni metals in eleven chondrites. Note that most chondrites show bimodal distribution of alteration degrees in their histograms.

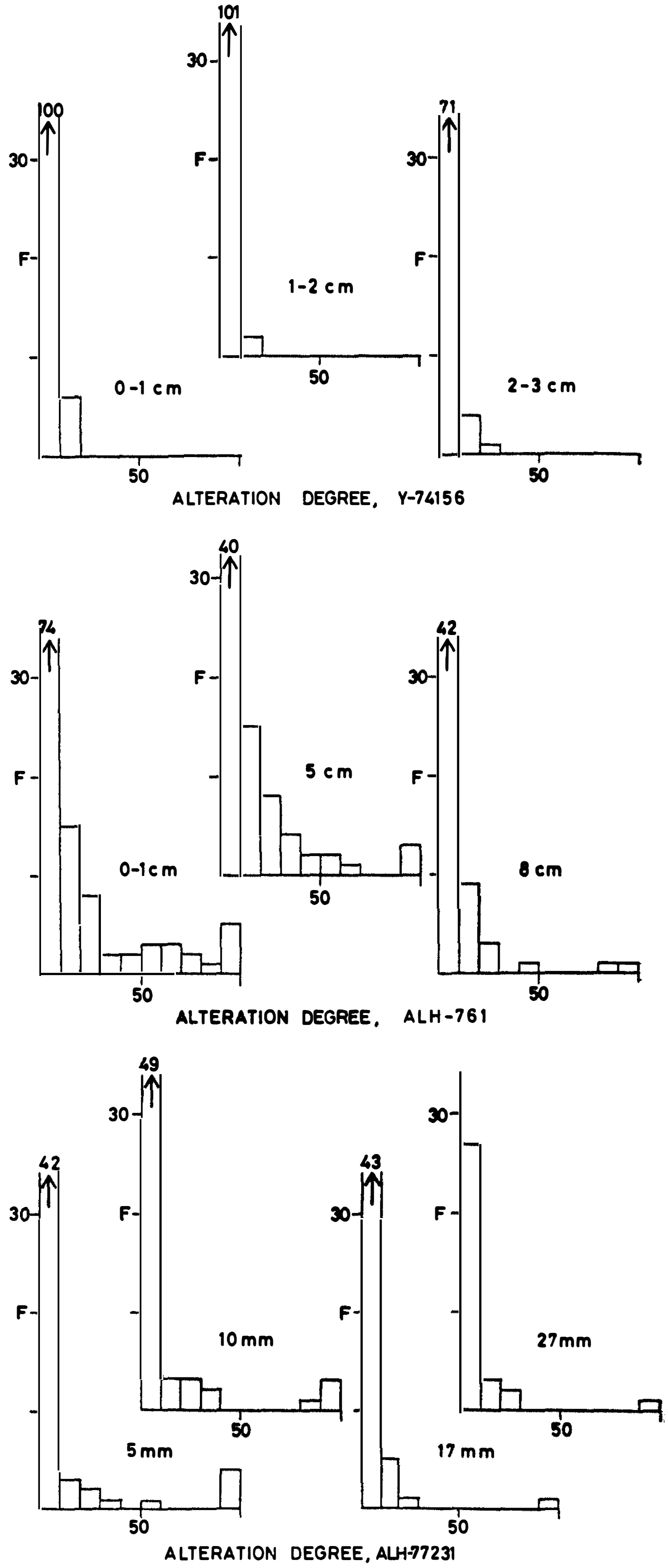

Fig. 3. Change in distribution of alteration degrees of Fe-Ni metals from the surface to the interior of three chondrites, Y-74156, ALH-761, and ALH-77231. Distance from the surface is shown in the histograms.

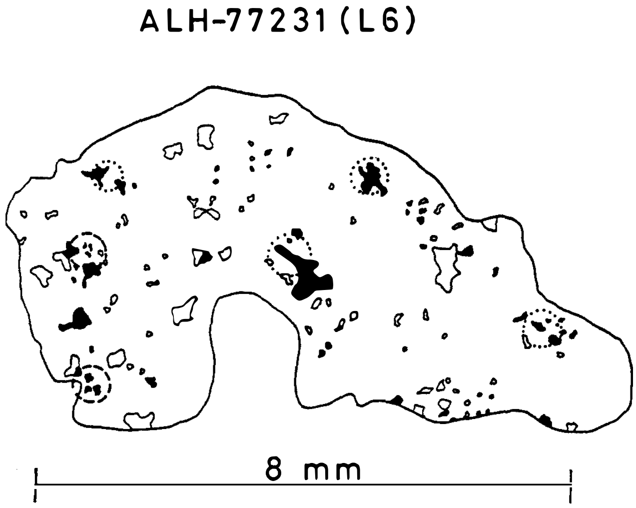

Fig. 4. Sketch of a thin section of the ALH-77231 chondrite (5 mm from the surface of the meteorite), showing the distribution of Fe-Ni metal grains (black portion) and troilite grains (white portions) larger than a few tens of microns across. Two areas shown by dash-circles include intensely-altered metal grains, four areas shown by dot-circles include moderately-altered metal grains, and metal grains outside these circles are very fresh.

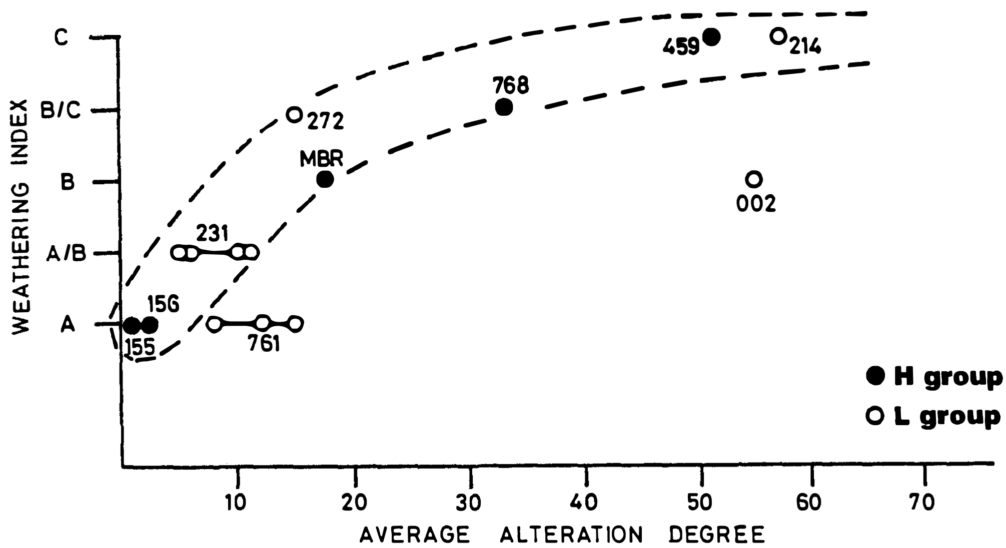

Fig. 5. Correlation between weathering index and average alteration degree for ten chondrites, Y-74155(155), Y-74156(156), Y-74459(459), MBR-761(MBR), ALH-761(761), ALH-768(768), ALH-77002(002), ALH-77214(214), ALH-77231(231), and ALH-77272 (272). Most chondrites are plotted in a zone shown by dash-line, and two chondrites, ALH-761 and ALH-77002, deviate from the correlation zone, suggesting that the two chondrites are wrongly classified in the A-B-C system.

Fe-Ni metal grains in the small areas might have been subjected to various kinds of strain such as lattice defects, shear twin, Neumann bands, martensite transformation, and so on. The Fe-Ni metal grains bearing the strain might have altered to the terrestrial alteration products more easily than those with no strain occurring outside the intensely-strained areas.

DODD and JAROSEWICH (1979) reported the occurrence of shock-melt pockets in ordinary chondrites. The shock-melt pockets are millimeters or submillimeters in size and occur locally in the chondrites. This size and localization of the shock-melt pockets support the idea that the localization of intensely-altered metal grains in the ALH-77231 (Fig. 4) was caused by impact shocks, although the chondrite does not include such shock-melt pockets.

4. Relationship between Weathering Index and Average Alteration Degree

Average alteration degrees of ordinary chondrites studied are summarized in Table 1 along with the weathering index, and Fig. 5 shows the relationship between them. There seems to be a positive correlation with upward-convex between them in Fig. 5; weathering indices, A, B, and C, correspond to the average alteration degrees, less than 5%, 10–20%, and more than 50%, respectively. Two exceptions, ALH-761 abd ALH-77002, deviate from the correlation zone, and they seem to have been classified into the wrong weathering indices.

Two chondrites, Y-74155 (H4) and Y-74156 (H4), may be a paired meteorite, because they show an average alteration degree similar to each other.

5. Alteration of Kamacite and Taenite

Fe-Ni metals and the alteration products in the ALH-77231 chondrite (L6) were analyzed using an electron-probe microanalyzer with the correction methods of standard ZAF. The Ni/(Fe+Ni) atomic ratios of metal grains range from 4% to 54%, sometimes showing compositional zoning from Ni-poor cores to Ni-rich rims. The alteration products are limonite including variable amounts of NiO and a small amount of SiO_2, and the representative chemical compositions are shown in Table 2. The Ni/(Fe+Ni) atomic ratios for pairs of Fe-Ni metal and limonite coexisting in a metal grain are shown by tie lines in Fig. 6. The ratios for limonites coexisting with kamacite are low, and for those coexisting with taenite are high.

As already stated in Section 3, intensely-altered Fe-Ni metal grains occur within localized small areas in a chondrite; the intensely-altered areas include highly-altered (about 100% in alteration degree) kamacite grains and moderately-altered (20–60%)

Table 2. Representative chemical composition of limonites in ALH-77231.

	Limonite			Limonite	
SiO_2	1.77	1.17	MgO	0.48	0.19
TiO_2	0.00	0.00	CaO	0.25	0.08
Al_2O_3	0.00	0.00	Na_2O	0.00	0.00
Cr_2O_3	0.00	0.00	K_2O	0.00	0.02
Fe_2O_3*	70.52	73.34	P_2O_5	0.00	0.13
NiO	3.30	4.44	H_2O**	23.65	20.60
MnO	0.03	0.03			
			Total	100.00	100.00

* All Fe as Fe_2O_3.

** The contents of H_2O (probably including variable amounts of SO_3 and Cl (GOODING, 1981)) were assumed to be the difference between 100 wt% and the sum of other components.

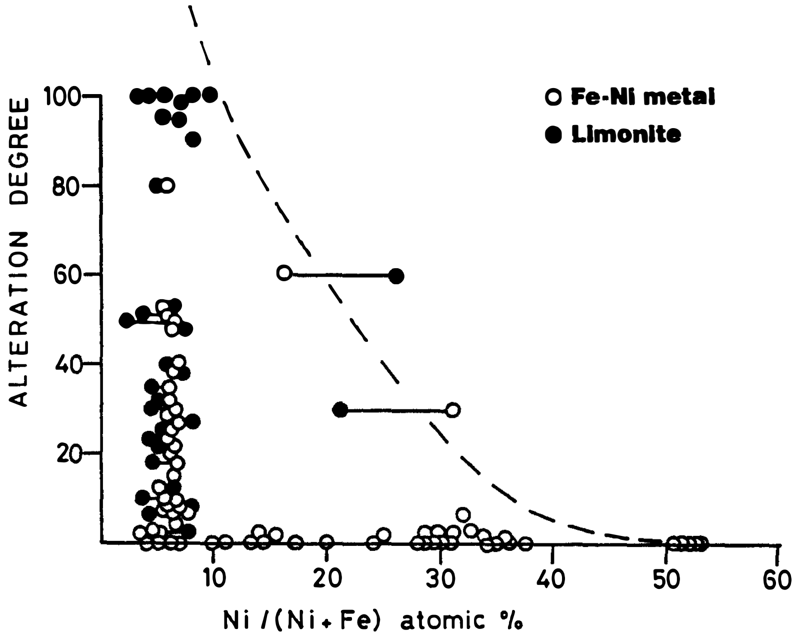

Fig. 6. Alteration degrees of Fe-Ni metal grains in the ALH-77231 chondrite (L6) are plotted against the Ni/(Ni+Fe) atomic percents of Fe-Ni metal (open circles) and limonite (closed circles). Pairs of Fe-Ni metal and limonite coexisting in a grain are shown by tie lines. Note that the alteration degrees seem to be dependent on the Ni contents of Fe-Ni metals and this is shown by a dash line described by free hand.

taenite grains, and the moderately-altered areas include moderately-altered (10–20% in alteration degree) kamacite grains and slightly-altered (less than a few %) taenite grains, although the areas outside the intensely- and moderately-altered areas include slightly-altered or alteration-free kamacite and taenite grains. Figure 6 suggests that the alteration degrees of Fe-Ni metals depend upon the Ni contents of the metals; the alteration of kamacite to limonite seems to be more than 10 times faster than that of taenite with 30–40% Ni, and more than 100 times faster than that of taenite with about 50% Ni.

6. Difference in Alteration among H, L, and LL Chondrites

Generally, H chondrites include large amounts of kamacite and small amounts of taenite, and LL chondrites are the reverse. L chondrites are intermediate between the two. On the assumption that average Ni contents of kamacite and taenite in ordinary chondrites are 7 and 35 wt%, respectively, the wt% ratios of kamacite to taenite in average chondrites are 9.3 for H chondrites, 2.4 for L chondrites, and 0.3 for LL chondrites (Table 3). Considering that the alteration rate of kamacite is more than ten times faster than that of taenite, the difference in kamacite/taenite wt% ratios among H, L, and LL chondrites should result in the difference in the average alteration degrees among them on an assumption that all conditions during the alteration were the same; the average alteration degrees for H chondrites must be more than ten times larger than those for LL chondrites, and those for L chondrites

Table 3. Average contents (wt%).

	Total Fe[1)]	FeO[1)]	FeS[1)]	Fe[1)]	Ni[1)]	Kamacite[2)]	Taenite[2)]
H	27.91	11.71	5.45	15.80	1.70	15.80	1.70
L	21.70	15.13	6.04	6.10	1.10	5.07	2.13
LL	20.35	19.86	5.27	1.33	0.95	0.54	1.74

[1)]HARAMURA *et al.* (1983); [2)]Average Ni contents of kamacite (7 wt%) and taenite (35 wt%).

Table 4. Frequency (%) of weathering index for each H, L, and LL groups of equilibrated chondrites (petrological types 4, 5, and 6) in Yamato-74 series and ALH-76, -77, -78 series.

	A	A/B	B	B/C	C
H group (N=167)	11.4	15.6	29.9	7.8	35.3
L group (N=107)	22.4	14.0	35.5	12.1	15.9
LL group (N=13)	61.5	7.7	23.1	7.7	0.0

N: Number of chondrites.
Data source: YANAI and KOJIMA (1987).

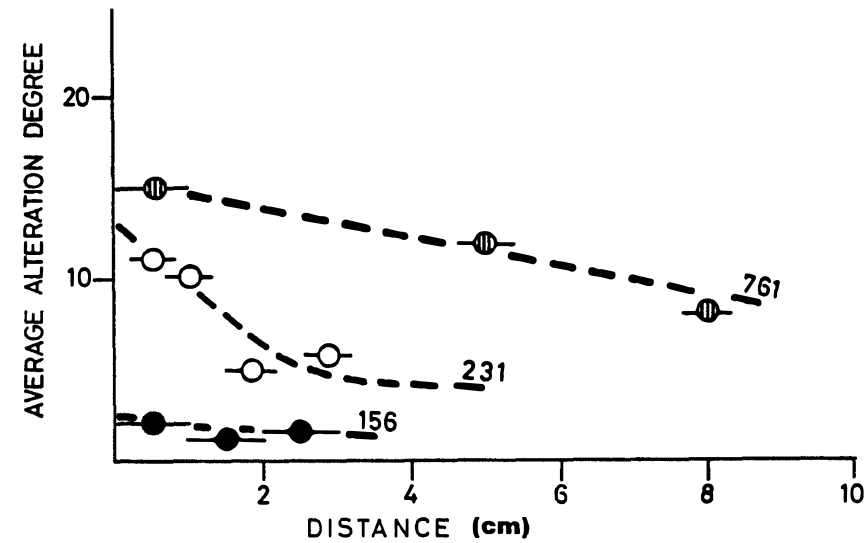

Fig. 7. Change in average alteration degrees from the surface to the interior of three chondrites, Y-74156(156), ALH-761(761) and ALH-77231(231). Uncertainty of distance is shown by horizonatl bars. The change of each chondrite is indicated by dash lines.

are intermediate between H and LL.

The frequency of weathering index for H, L, and LL chondrites from Yamato-74 and ALH-76, -77, and -78 meteorite collections is shown in Table 4. For H chondrites index C is predominant with rare index A, for L chondrites index B is predominat, and for LL chondrites index A is predominat with no index C. The difference in frequency of weathering index among H, L, and LL chondrites can be explained by the difference in kamacite/taenite wt% ratios among them.

7. Difference in Average Alteration Degree between Surface and Interior

In order to know the difference in average alteration degrees between the surface and interior in a meteorite, we measured them for three meteorites, Y-74156 (H4, radius=3.5 cm), ALH-77231 (L6, radius=5 cm), and ALH-761 (L6, radius=8 cm), and the results are shown in Table 1 and Fig. 3 and summarized in Fig. 7. Average alteration degrees of the surfaces are larger than those of the interiors, but the difference between them is a factor of <2 (Fig. 7). This suggests that meteorites with intensely-altered surface have the intensely-altered interiors, also; meteorites with the surface of weathering index C have the interiors with weathering index C or B/C, and meteorites with the surface of weathering index B have the interiors of weathering index B or A/B.

8. Average Alteration Degree and Terrestrial Age

Terrestrial ages of ordinary chondrites studied (NISHIIZUMI *et al.*, 1989) are shown in Table 1. The average alteration degrees are plotted against the terrestrial ages in Fig. 8. As already stated in Section 5, alteration of Fe-Ni metals is faster for H chondrites than for L chondrites. Therefore, the examination for correlation between average alteration degrees and the terrestrial ages should be treated separately for H and L chondrites. For the case of H chondrites studied, the alteration rate (average alteration degree divided by the terrestrial age) could be the same for four chondrites, Y-74156, MBR-761, ALH-768, and Y-7301 within the error bars of terrestrial ages. However, the alteration rate for Y-74459 is the largest among H chondrites studied and deviates from the alteration rate common for the other H chondrites. The Y-

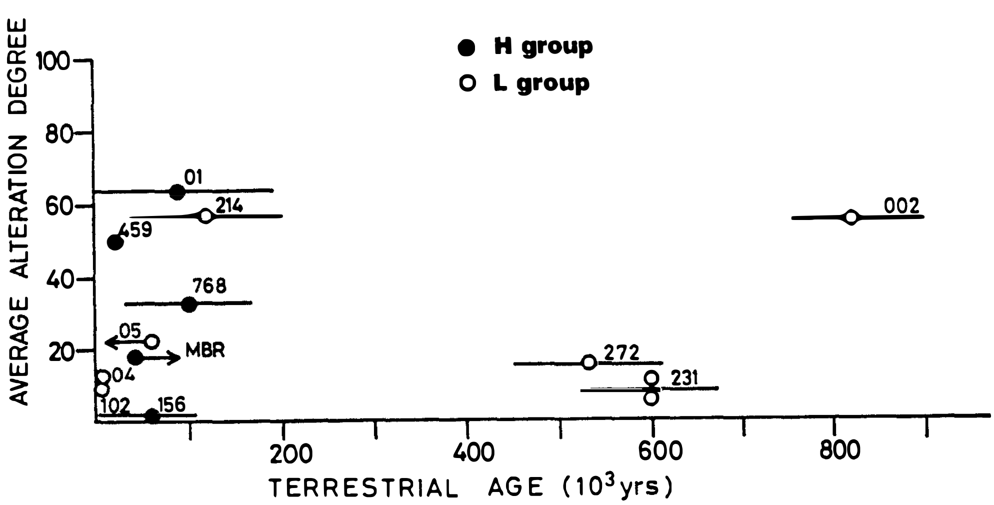

Fig. 8. Average alteration degrees of H chondrites (closed circles) and L chondrites (open circles) are plotted against the terrestrial ages. Horizontal bars are uncertainty of terrestrial ages, and horizontal arrows show the larger or smaller range. Abbreviations are; Y-7301(01), Y-7304(04), Y-7305(05), Y-74156(156), Y-74459(459), Y-75102(102), MBR-761 (MBR), ALH-768(768), ALH-77002(002), ALH-77231(231), and ALH-77272(272).

74459 chondrite seems to have suffered intense impact shocks because the olivine grains in the chondrite show remarkable wavy extinction under the microscope. This suggests that alteration rate depends upon the degree of impact shocks which the chondrite had suffered in or on the parent body prior to their fall on the Earth.

For the case of L chondrites, the alteration rate varies more widely than for H chondrites (Fig. 8). In the same way as H chondrites, the alteration rate for L chondrites may depend upon the degrees of impact shocks.

NISHIIZUMI *et al.* (1989) compared the terrestrial ages with the weathering indices for ordinary chondrites and concluded that there is no correlation between them. We support their conclusions for H and L chondrites.

9. Conclusion

(1) Weathering indices A, B, and C correspond to the average alteration degrees, less than 5%, 10–20%, and more than 50%, respectively.

(2) The alteration degrees of Fe-Ni metals are localized in most ordinary chondrites and the localization may be due to impact shocks which the chondrites had suffered in or on the parent body prior to their fall on the Earth.

(3) Fe-Ni metals in most chondrites show bimodal distribution in the histograms of the alteration degrees. The bimodality seems to have been caused by the localization of highly-altered metal grains.

(4) The alteration degrees depend upon the Ni contents of Fe-Ni metals. Kamacite alters to limonite more than ten times faster than taenite.

(5) Fe-Ni metals in H, L, and LL chondrites altered rapidly, intermediately, and slowly, respectively, as the kamacite/taenite wt% ratios decrease in the order of H, L, and LL.

(6) The average alteration degrees of the surfaces of chondritic meteorites are larger than those of the interiors although the difference in the degree between them is smaller than a factor of two.

(7) There is no correlation between the average alteration degrees and the terrestrial ages for both cases of H and L chondrites. The average alteration degrees seem to depend more largely upon the degrees of impact shocks than upon the terrestrial ages.

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