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COMPARATIVE STUDY ON THE MAJOR ELEMENT CHEMICAL COMPOSITIONS OF ANTARCTIC CHONDRITES TO THOSE OF NON-ANTARCTIC FALLS WITH REFERENCE TO TERRESTRIAL WEATHERING

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Abstract: Antarctic ordinary chondrites contain variable amounts of Fe_2O_3 and water as terrestrial weathering products. The Fe_2O_3 contents have a positive correlation with water contents, and a negative correlation with metallic Fe. Therefore, oxygen and water were added to Antarctic chondrites during weathering to form limonitic alteration from metallic iron. Other major elements and total Fe slightly decrease with increasing Fe_2O_3. This decrease is caused by the "dilution" effect due to additional water and oxygen, suggesting that most of the Antarctic chondrites seem to have undergone terrestrial weathering in a quasi-closed system insofar as major elements are concerned. Weathering index has minimal or no relation with the Fe_2O_3 contents of chondrites. Extensive weathering obscures petrographic features of some chondrites, leading to the misclassification, and they are revised on the basis of UC diagram. The major element compositions of Antarctic ordinary chondrites are the same as those of non-Antarctic falls, and they show slight difference in Mg and Na contents among H, L, and LL chondrites; H chondrites have the highest Mg/Si ratio and the lowest Na/Si ratio on average. Some LL chondrite breccias have higher K contents than non-brecciated LL chondrites.

1. Introduction

Antarctic meteorites have experienced variable degree of weatherings. Metal is most susceptible to terrestrial weathering, which has altered to limonitic materials including akaganeite, goethite, amorphous materials etc. (GOODING, 1981; BUCHWALD and CLARKE, 1987). Terrestrial weathering can cause chemical changes in major and minor element compositions (GOODING, 1989; KOEBERL and CASSIDY, 1991; VELBEL *et al.*, 1991), sometimes obscuring geochemistry and cosmochemistry. It results in misclassification of meteorites, especially for unequilibrated chondrites. Therefore, it is very important in the study of chemical compositions to know to what extent terrestrial weathering effects in Antarctic meteorites. As the degrees of weathering may be best estimated by the amounts of Fe_2O_3, the weathering effects will be discussed on the basis of Fe_2O_3 contents in this paper.

Four hundred ninety three Antarctic chondrites were analyzed by one of the authors (H. HARAMURA) with the standard wet chemical method, and the results were presented in the "Catalog of the Antarctic Meteorites" compiled by YANAI and KOJIMA (1995). There are 401 chondrites; E, H, L, LL, and C chondrites are 5, 161, 155, 53, and 28, respectively. JAROSEWICH (1990) presented the major element chemical compositions of 99 non-Antarctic ordinary chondrite falls. From them, we selected 96 ordinary chondrites which do not contain Fe_2O_3, and in order to know the weathering effects on major element compositions of chondrites we compared the chemical compositions of 401 Antarctic chondrites (duplicated data of four chondrites are given in the catalog and we selected data with a lower Fe_2O_3 content) with those of 96 non-Antarctic falls.

2. Fe_2O_3, Metallic Fe and Water Contents

2.1. Fe_2O_3 and water

In Antarctic ordinary chondrites, various amounts of metallic iron have altered to limonites ($Fe_2O_3 \cdot 1\text{–}5H_2O$) (IKEDA and KOJIMA, 1991). Although clay minerals occur in some Antarctic chondrites as terrestrial weathering products (GOODING, 1986) or rarely as pre-terrestrial alteration products (HUTCHISON *et al.*, 1987), they are volumetrically small (GOODING, 1986), suggesting that most of the Fe_2O_3 and water occur as limonites. Fe_2O_3 and water contents are plotted in Fig. 1, and Fe_2O_3 and $H_2O(+)$ range from 0–12.2 and from 0–3.7 wt%, respectively. Figure 1 shows that the Fe_2O_3 contents of H and L chondrites are approximately in proportion to their water contents, and the average proportion of Fe_2O_3:$H_2O(+)$ is about 1:2 in molar ratio for H chondrites and 1:2.5 for L and LL chondrites. This difference in molar ratio between chemical groups of chondrites may not be significant because the data in Fig. 1 scatter largely for each group. The large scatter is partly due to the uncertainty of Fe_2O_3 determination; Fe_2O_3 is obtained by difference and is the products of additive errors.

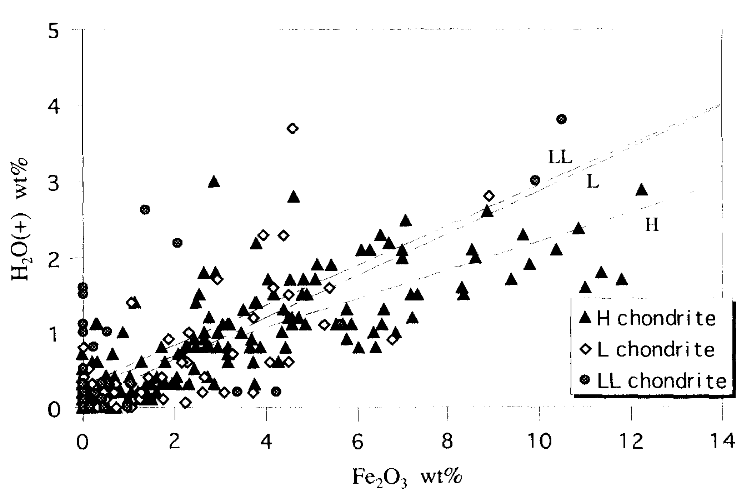


Fig. 1. $H_2O(+)$ (wt%)-Fe_2O_3 (wt%) relation of Antarctic ordinary chondrites. Three broken lines are regression lines obtained by the least square fitting method for H, L, and LL chondrites.

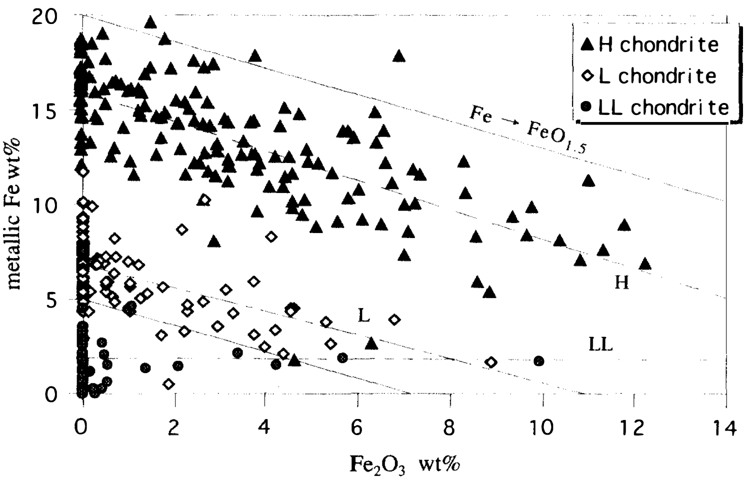


Fig. 2. Metallic Fe (wt%)–Fe_2O_3 (wt%) relation of Antarctic ordinary chondrites. Solid lines are alteration lines changing metallic Fe to $FeO_{1.5}$. Broken lines are obtained by the least square fitting method for H, L, and LL chondrites.

2.2. Fe_2O_3 and metallic Fe

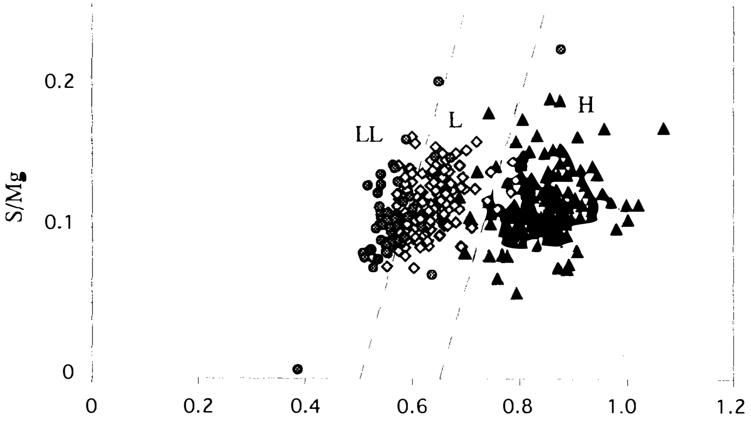
The Fe_2O_3 contents of H and L chondrites are in negative proportion to their metallic Fe contents, as shown in Fig. 2. The regression lines for H and L chondrites shown in Fig. 2 are nearly parallel to the line which shows alteration of metallic Fe to Fe_2O_3. This means that metallic Fe in Antarctic H and L chondrites was oxidized to Fe_2O_3. Oxidation of other components such as FeS or FeO was minimal. However, the Fe_2O_3 contents of LL chondrite do not plot along a line showing alteration of metallic Fe to Fe_2O_3, and some LL chondrites plot in the L chondrite region. In addition, some H and L chondrites plot outside their own regions, as shown in Fig. 2. These chondrites have unusually low or high contents of metal or Fe_2O_3, and thus we need to review their compositions and revise their classification.

3. Examination of Classification for Antarctic Ordinary Chondrites

The classification of Antarctic chondrites into chemical groups and petrologic types has been carried out mostly on the basis of their petrographic characteristics and mineral compositions. However, intense weathering of Antarctic ordinary chondrites sometimes obscures their original features, especially for unequilibrated chondrites, leading to misclassification of some meteorites.

Generally speaking, equilibrated ordinary chondrites are classified into a chemical group based on their olivine compositions; with fayalite contents of 16–20% for H chondrite, 21–25% for L chondrite, and 26–31% for LL chondrite. Traditionally, unequilibrated ordinary chondrites, as well as equilibrated ordinary chondrites, were classified based on UC diagram (VAN SCHUMS and WOOD, 1967). However, group assignment of some unequilibrated ordinary chondrites (for example, Bishunpur, Krymka, Manych, etc.; they are L3 or LL3) was in doubt (HUSS *et al.*, 1981), and thus DODD and JAROSEWICH (1979) presented a new criteria for grouping of L and LL chondrites based on S/Mg–Fe/Mg plotting, concluding that shock mobilization is responsible for much of metallic iron and sulfur variation obtained in L and LL chondrites. Figure 3 is S/Mg–Fe/Mg diagrams in which Antarctic ordinary chondrites (Fig. 3a) and non-Antarctic falls (Fig. 3b) plot. The non-Antarctic L and LL chondrites seem to be well grouped, as shown in Fig. 3b, except for one chondrite (Knyahinya, L5 breccia) which plots in the LL region. However, Fig. 3a shows that Antarctic L and LL chondrites, as well as H chondrites, can not be grouped by the S/Mg–Fe/Mg diagram, indicating that the diagram can not be used for classification of Antarctic ordinary chondrites including unequilibrated chondrites. Therefore, we classify ordinary chondrites based on Si-normalized UC diagram, and all Antarctic ordinary chondrites plot in Fig. 4a, where Fe_2O_3 is taken to be originally metallic Fe. The Antarctic ordinary chondrites of each chemical group overlap with one another, as shown in Fig. 4a; a few L chondrites plot in H chondrite and LL chondrite ranges, several LL chon-

(a) Antarctic



(b) Non-Antarctic

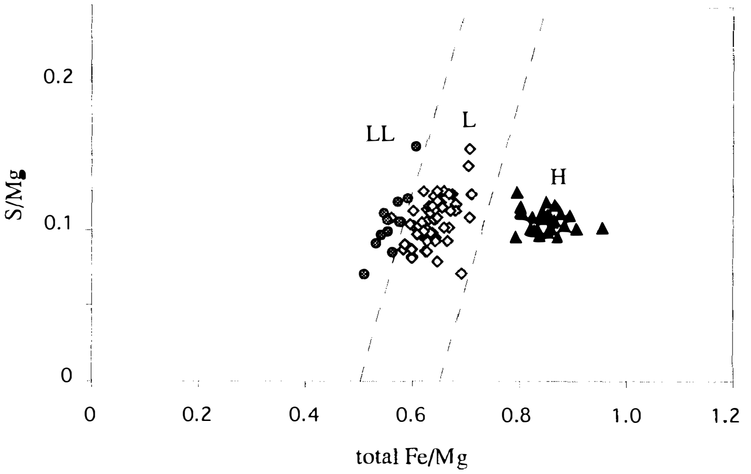
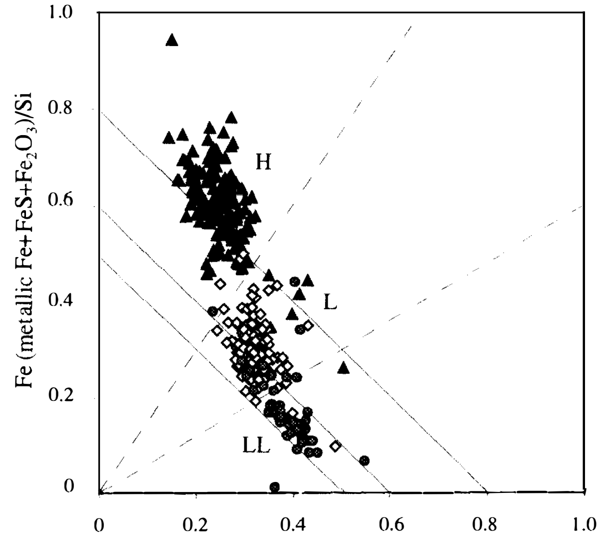


Fig. 3. S/Mg–total Fe/Mg relation (in atomic) of (a) Antarctic ordinary chondrites and (b) non-Antarctic falls (JAROSEWICH, 1990). Broken lines are boundaries between groups for non-Antarctic falls which are drawn by free hands.

drites plot in L chondrite range, and some chondrites plot outside each group range. We call them "chondrites with unusual iron contents" in this paper and list them in Appendix. Non-Antarctic falls of L and LL chondrites also overlap with one another (Fig. 4b). The unusual iron contents including redox state of iron may be caused by the following factors; (1) sampling effect, meaning that the constituent minerals such as metal, sulfides etc. distribute heterogeneously in unshocked samples, (2) the unusual nature may be partly explained by heterogeneous occurrence of metal or sulfide veins and/or nodules in some shocked samples, (3) regolithic breccia also can result

(a) Antarctic



(b) Non-Antarctic

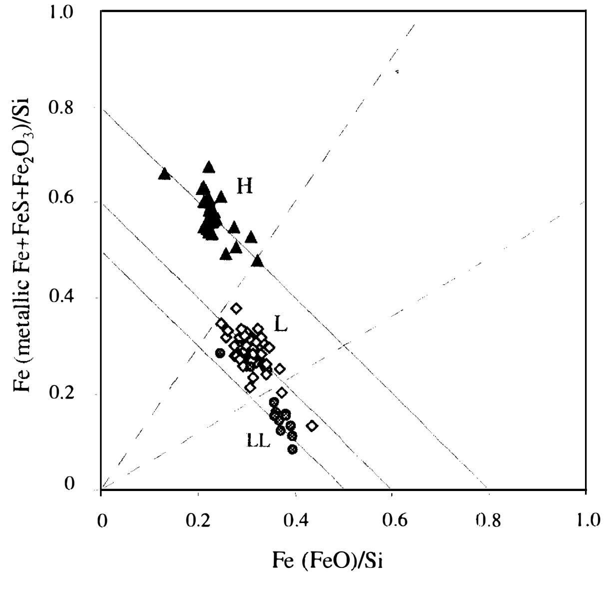


Fig. 4. The Si-normalized UC diagram (in atomic) for ordinary chondrites: (a) Antarctic meteorites, and (b) non-Antarctic falls by JAROSEWICH *(1990) except for chondrites with high* Fe_2O_3 *contents. The boundaries between chemical groups are drawn by free hands.*

in the unusual composition, and (4) difficulty of wet chemical analysis for the samples including all metallic Fe, sulfidized Fe, FeO and Fe_2O_3.

4. Compositional Change during Terrestrial Weathering

It is well known that minor and trace element compositions of chondrites have changed during terrestrial weathering (GIBSON and BOGARD, 1978; GOODING, 1981, 1986, 1989; VELBEL, 1988; STRUEMPLER, 1990; SHINONAGA *et al.*, 1994; BURNS *et al.*, 1995), despite assertions to the contrary (DENNISON *et al.*, 1986; LIPSCHUTZ and SAMUELS, 1991). VELBEL (1988) stated that two evaporate-bearing carbonaceous chondrites show some depletions of Ca by the evaporate formation. GIBSON and BOGARD (1978) showed that Na content of the Holbrook (L6) chondrite decreases during terrestrial weathering. GOODING (1981) concluded that net loss of Fe, Ni, S, and, to a lesser extent, Mg by weathering seems entirely possible. It is evident that the formation of Si-Ni-S-bearing limonite, hydrous clay mineraloids, and evaporates in or on chondrites causes change of major element compositions to "some" extent. In order to evaluate the extent to change, we examine the major element compositions of Antarctic chondrites which are selected as "usual" ordinary chondrites, excluding the "chondrites with unusual iron contents" listed all in Appendix.

The total Fe contents of Antarctic H chondrites slightly decrease with increasing Fe_2O_3 contents, as shown in Fig. 5a; total Fe contents of H chondrites with negligible Fe_2O_3 are about 28–29 wt% on average, and those with 10–12 wt% Fe_2O_3 are about 25–26 wt%. This decrease of total Fe contents may be explained by a "dilution" effect due to additional water and oxygen contents that formed limonites from metallic iron during terrestrial alteration. This situation is the same for L chondrites and probably for LL chondrites. Thus, any iron contents of Antarctic ordinary chondrites seem not to have been lost during weathering, and we conclude that total Fe contents of Antarctic chondrites studied here have remained constant and the variations are within the analytical errors. Although metallic Fe contents of H and L chondrites are clearly in negative proportion to their Fe_2O_3 contents (Fig. 2), their metallic Ni contents slightly decrease with increasing Fe_2O_3 in parallel to the dilution line (Fig. 5b). This suggests that kamacites in H and L chondrites have changed to Fe_2O_3 during weathering, but most of taenites have not altered. This is consistent with the conclusion obtained by IKEDA and KOJIMA (1991) that kamacites were more easily altered to limonites than taenites. As shown in Fig. 5a, H chondrites which contain the most abundant kamacite among ordinary chondrites include the most abundant Fe_2O_3 as a whole, LL chondrite containing the least kamacite include the least Fe_2O_3, and L chondrites are intermediate.

FeS contents of Antarctic chondrites seem to remain constant or slightly decrease with increasing Fe_2O_3 (Fig. 5c). Other components of Antarctic ordinary chondrites such as, SiO_2, MgO, and Na_2O show a negative correlation with their Fe_2O_3 contents; they are plotted roughly parallel to the dilution lines (Fig. 5d, e,f). These elements seem to remain constant during the weathering except for the dilution effect.

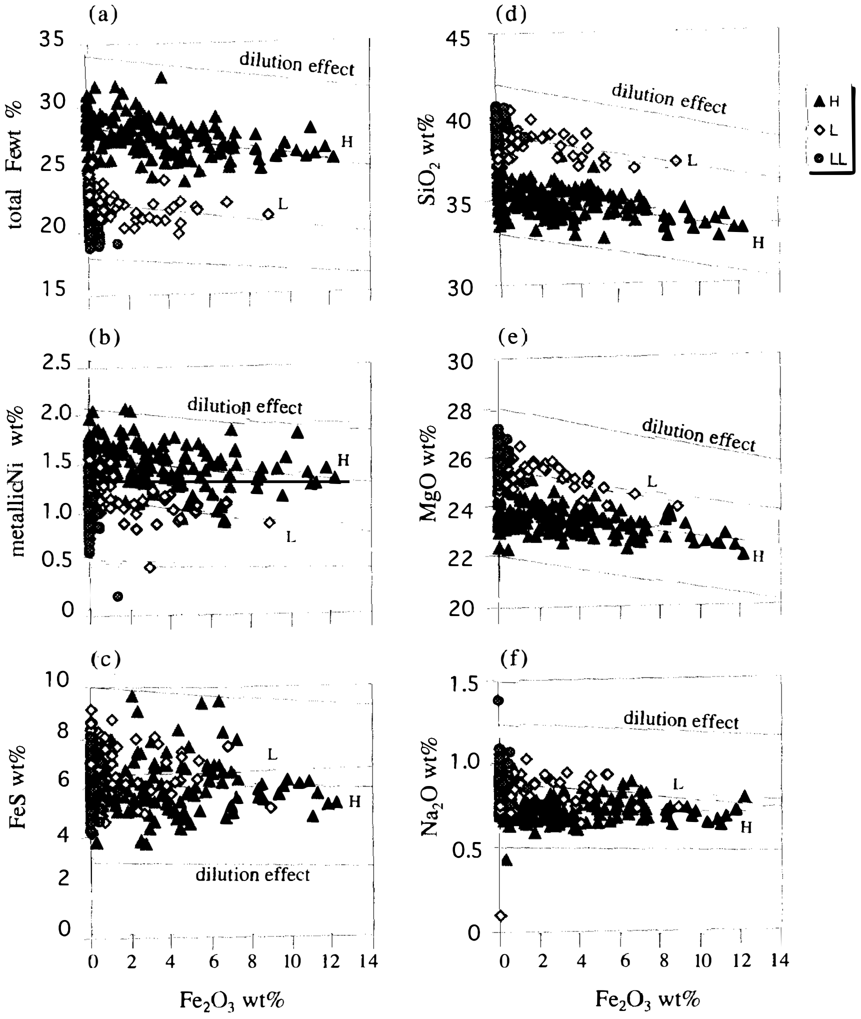


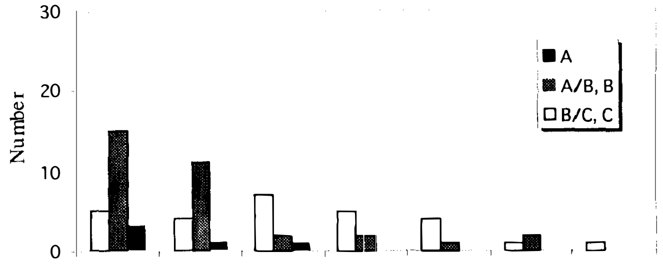
Fig. 5. Relation of major element contents versus Fe_2O_3 (wt%) for Antarctic ordinary chondrites except for chondrites listed in Appendix. Figure 5a, b, c, d, e, and f are for total Fe, metallic Ni, FeS, SiO_2, MgO, and Na_2O, respectively. Solid lines mean dilution effect. The dilution line was calculated on the assumption that 2Fe change to $Fe_2O_3 \cdot 2.5H_2O$ which includes both H_2O (+) and (−). Other marks are the same those in Fig. 1.

5. Relationship Between Fe_2O_3 Contents and Weathering Index

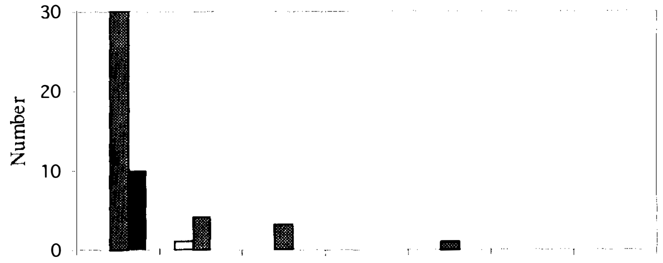
The weathering index (A-B-C system) is generally used as an indicator of the degree of the weathering for meteorite finds including Antarctic chondrites, but its application is largely subjective (GOODING, 1989). In addition, the degree of weathering depends upon the amounts of kamacite in a given sample (IKEDA and KOJIMA, 1991) so that it is very difficult to compare the weathering index between chemical groups. Thus, the comparison of weathering index is meaningful merely for chondrites belonging to a same chemical group which has nearly the same amount of kamacite.

The weathering index of Antarctic chondrites is shown in YANAI and KOJIMA (1995), and the relationship of weathering index with Fe_2O_3 is shown for H, L, and

(a) H chondrite



(b) L chondrite



(c) LL chondrite

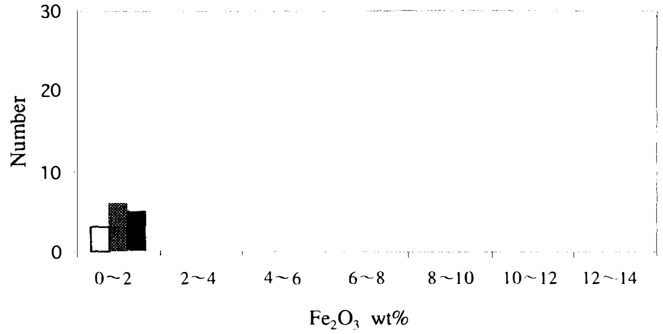


Fig. 6. Distribution of weathering index of Antarctic ordinary chondrites in relation to their Fe_2O_3 (wt%). Figure 6a, b, and c are for H, L, and LL chondrites, respectively.

LL chondrites separately in Fig. 6a–c. There seems to be a weak correlation between the weathering index and Fe_2O_3 contents for H chondrites. However there is no correlation for L and LL chondrites. This may be due partly to "sampling" effect, which means that fresh samples of Antarctic meteorites might have been selected from cores of meteorites for chemical analysis, and partly due to uncertainty to determine the weathering index without application of a quantitative method (IKEDA and KOJIMA, 1991).

6. Average Composition of Chemical Groups

Average compositions of chemical groups were obtained using Antarctic ordinary chondrites having only usual compositions, except for "chondrites with unusual Fe contents" listed in Appendix. They are shown in Table 1 along with those of non-Antarctic falls obtained by JAROSEWICH (1990). The average compositions of Antarctic

*Table 1. Average chemical compositions (wt%) of Antarctic chondrites (*Yanai *and* Kojima*, 1995) non-Antarctic falls (*Jarosewich*, 1990). The Antarctic chondrites are averaged, using chondrites with usual compositions except for those of listed in Appendix.*

	Antarctic ordinary chondrites						Jarosewich (1990)		
	H (154)		L (147)		LL (39)		H	L	LL
		s.d.		s.d.		s.d.			
SiO_2	35.06	*0.96*	38.32	*0.81*	39.77	*0.55*	36.60	39.72	40.60
TiO_2	0.08	*0.02*	0.10	*0.03*	0.11	*0.04*	0.12	0.12	0.13
Al_2O_3	2.30	*0.47*	2.43	*0.40*	2.61	*0.47*	2.14	2.25	2.24
Cr_2O_3	0.38	*0.08*	0.45	*0.08*	0.48	*0.11*	0.52	0.53	0.54
Fe_2O_3	3.14	*2.99*	0.64	*1.46*	0.10	*0.26*			
FeO	10.32	*1.58*	14.70	*1.08*	18.84	*1.32*	10.12	14.46	17.39
MnO	0.28	*0.07*	0.31	*0.06*	0.31	*0.06*	0.31	0.34	0.35
NiO	0.01	*0.09*	0.01	*0.08*	0.08	*0.26*			
MgO	23.56	*0.60*	25.42	*0.51*	25.99	*0.53*	23.26	24.73	25.22
CaO	1.61	*0.21*	1.79	*0.18*	1.82	*0.11*	1.74	1.85	1.92
Na_2O	0.74	*0.08*	0.87	*0.10*	0.93	*0.10*	0.86	0.95	0.95
K_2O	0.08	*0.01*	0.09	*0.02*	0.10	*0.03*	0.09	0.11	0.10
P_2O_5	0.23	*0.11*	0.24	*0.48*	0.26	*0.12*	0.27	0.22	0.22
$H_2O(+)$	0.86	*0.69*	0.07	*0.11*	0.36	*0.56*	0.32	0.37	0.51
$H_2O(-)$	0.21	*0.18*	0.26	*0.11*	0.11	*0.15*	0.12	0.09	0.20
FeS	6.04	*1.07*	6.49	*0.98*	5.84	*0.94*	5.43	5.76	5.79
Fe	13.62	*2.94*	6.31	*1.56*	1.50	*0.96*	15.98	7.03	2.44
Ni	1.46	*0.21*	1.10	*0.16*	0.83	*0.24*	1.74	1.24	1.07
Co	0.06	*0.02*	0.04	*0.01*	0.03	*0.01*	0.08	0.06	0.05
Total	100.04	*0.29*	100.13	*0.31*	100.09	*0.27*	99.99	99.99	99.92
Total Fe	27.67	*1.61*	22.31	*1.19*	19.93	*0.59*	27.45	21.93	19.63

	Antarctic E and carbonaceous chondrites										
	EH (5)		CI (1)	CM (13)		CR (2)		CO (8)		CV (1)	CK (3)	
		s.d.			s.d.		s.d.		s.d.			s.d.
SiO_2	33.80	*1.57*	26.99	27.95	*2.16*	32.05	*0.25*	32.51	*1.65*	32.84	32.37	*1.27*
TiO_2	0.11	*0.04*	0.23	0.16	*0.04*	0.10	*0.01*	0.15	*0.05*	0.11	0.15	*0.09*
Al_2O_3	2.49	*0.49*	2.26	2.66	*0.53*	2.13	*0.38*	3.41	*1.15*	3.16	2.69	*0.40*
Cr_2O_3	0.39	*0.07*	0.48	0.44	*0.07*	0.46	*0.08*	0.51	*0.02*	0.49	0.49	*0.05*
Fe_2O_3	1.79	*3.97*	2.32	6.77	*7.48*	6.34	*0.76*	4.30	*6.04*	0.47	10.78	*5.00*
FeO	4.88	*5.80*	10.85	12.75	*5.94*	16.64	*9.68*	19.58	*6.12*	24.59	17.27	*4.04*
MnO	0.25	*0.02*	0.31	0.24	*0.04*	0.22	*0.04*	0.23	*0.05*	0.17	0.24	*0.04*
NiO	0.00	*0.00*	1.28	0.07	*0.24*	0.89	*1.25*	0.21	*0.58*	0.00	0.00	*0.00*
MgO	18.38	*0.75*	20.19	20.23	*2.05*	23.25	*0.11*	23.88	*1.55*	24.45	25.22	*0.22*
CaO	1.09	*0.15*	2.04	1.92	*0.34*	1.85	*0.37*	2.09	*0.24*	2.51	2.38	*0.05*
Na_2O	0.73	*0.10*	0.87	0.33	*0.18*	0.26	*0.04*	0.34	*0.15*	0.41	0.36	*0.08*
K_2O	0.07	*0.03*	0.13	0.04	*0.01*	0.05	*0.01*	0.04	*0.02*	0.04	0.03	*0.02*
P_2O_5	0.33	*0.16*	0.36	0.27	*0.11*	0.30	*0.19*	0.24	*0.09*	0.44	0.15	*0.12*
$H_2O(+)$	4.60	*2.31*	8.01	11.40	*4.86*	4.15	*0.49*	2.62	*1.97*	0.60	1.10	*0.89*
$H_2O(-)$	1.09	*0.55*	3.94	3.10	*2.03*	0.80	*0.28*	1.23	*1.08*	0.70	0.67	*0.60*
FeS	14.02	*1.37*	20.08	9.55	*2.22*	3.00	*0.33*	4.94	*1.28*	6.02	4.73	*0.53*
Fe	14.29	*4.05*	0.00	0.87	*1.37*	6.92	*9.78*	2.60	*3.48*	2.35	0.00	*0.00*
Ni	1.50	*0.13*	0.00	1.01	*0.39*	0.74	*1.04*	1.07	*0.45*	1.24	1.39	*0.25*
Co	0.06	*0.01*	0.04	0.04	*0.01*	0.05	*0.00*	0.05	*0.01*	0.05	0.05	*0.01*
Total	99.87	*0.14*	100.38	99.80	*0.19*	100.20	*0.60*	100.00	*0.17*	100.64	100.07	*0.21*
Total Fe	28.24	*0.47*	22.81	21.58	*1.44*	26.19	*1.51*	23.96	*1.03*	25.62	23.97	*0.31*

Total numbers of chondrites are shown in parentheses.
The s.d. means standard deviation (1σ).

and non-Antarctic chondrites are very similar to each other. However, there are systematic differences in chemical compositions of average H, L, and LL chondrites between the Antarctic chondrites and non-Antarctic falls; the contents of SiO_2, TiO_2, Cr_2O_3, MnO, CaO, Na_2O, Ni, and Co are systematically higher for non-Antarctic falls than those for Antarctic chondrites. The Al_2O_3, MgO, FeS, and total Fe contents are lower for non-Antarctic falls than for Antarctic chondrites. These systematic differences between Antarctic chondrites and non-Antarctic falls may be caused either by terrestrial weathering or by interlaboratory difference.

In order to clarify this problem, we examined interlaboratory differences for the same samples. The chemical compositions of the same samples, two H, four L, and two LL chondrites, are presented both in the YANAI and KOJIMA (1995) and in JAROSEWICH (1990), and their average compositions are shown in Table 2. Considering that the analysis of meteorites is very difficult, we find that the agreement between the two laboratories is remarkable. However, there are minor but systematic differences in composition between the two laboratories; the contents of SiO_2, TiO_2, CaO, P_2O_5, Ni, and Co are higher for JAROSEWICH (1990) than for the YANAI and KOJIMA (1995), and the contents of Al_2O_3, MgO, FeS, and total Fe are lower for JAROSEWICH (1990), in all of meteorites which were analyzed by both researcher. This systematic difference is the same as those discussed above. Therefore, we conclude that the differences in composition of average H, L, and LL chondrites between Antarctic chondrites and non-Antarctic falls shown in Table 1 are due to the interlaboratory difference. The fact that no remarkable difference in average compositions of H, L, and LL chondrites is recognized between the Antarctic chondrites and non-Antarctic falls supports the conclusion that terrestrial weathering of Antarctic chondrites took place in a quasi-closed system under Antarctic conditions. The average compositions of EH and C chondrites are shown in Table 1 for reference, and average composition of non-Antarctic falls are shown only for CM and CV chondrites in JAROSEWICH (1990). Taking it into consideration that there is a systematic difference between the two laboratories, the average compositions of Antarctic CM and CV chondrites are very similar to those of non-Antarctic falls.

7. Comparison Between Ordinary Chondrite Groups

The Mg/Si atomic ratios of both Antarctic chondrites and non-Antarctic falls are shown in Fig. 7a and b, and they are similar to each other. However, the ratios are the highest for both Antarctic and non-Antarctic H chondrites in comparison to those for L and LL chondrites. This is consistent with the data obtained by WASSON (1974, p.17, Fig. II-2). Ca/Si ratios are smaller for Antarctic chondrites than for non-Antarctic chondrites (Fig. 7c, d), and this may be due to the interlaboratory difference, because CaO/SiO_2 weight ratios of ordinary chondrites are smaller for YANAI and KOJIMA (1995) than for JAROSEWICH (1990) (Table 2). Although the average Al/Si ratios of Antarctic and non-Antarctic chondrites are similar to each other, the ratios distribute more widely for Antarctic chondrites than for non-Antarctic falls (Fig. 7e, f). The Na/Si ratios of L and LL chondrites seem to be slightly higher, as a whole, than those of H chondrites both for Antarctic and non-Antarctic chondrites (Fig. 7g, h). This dif-

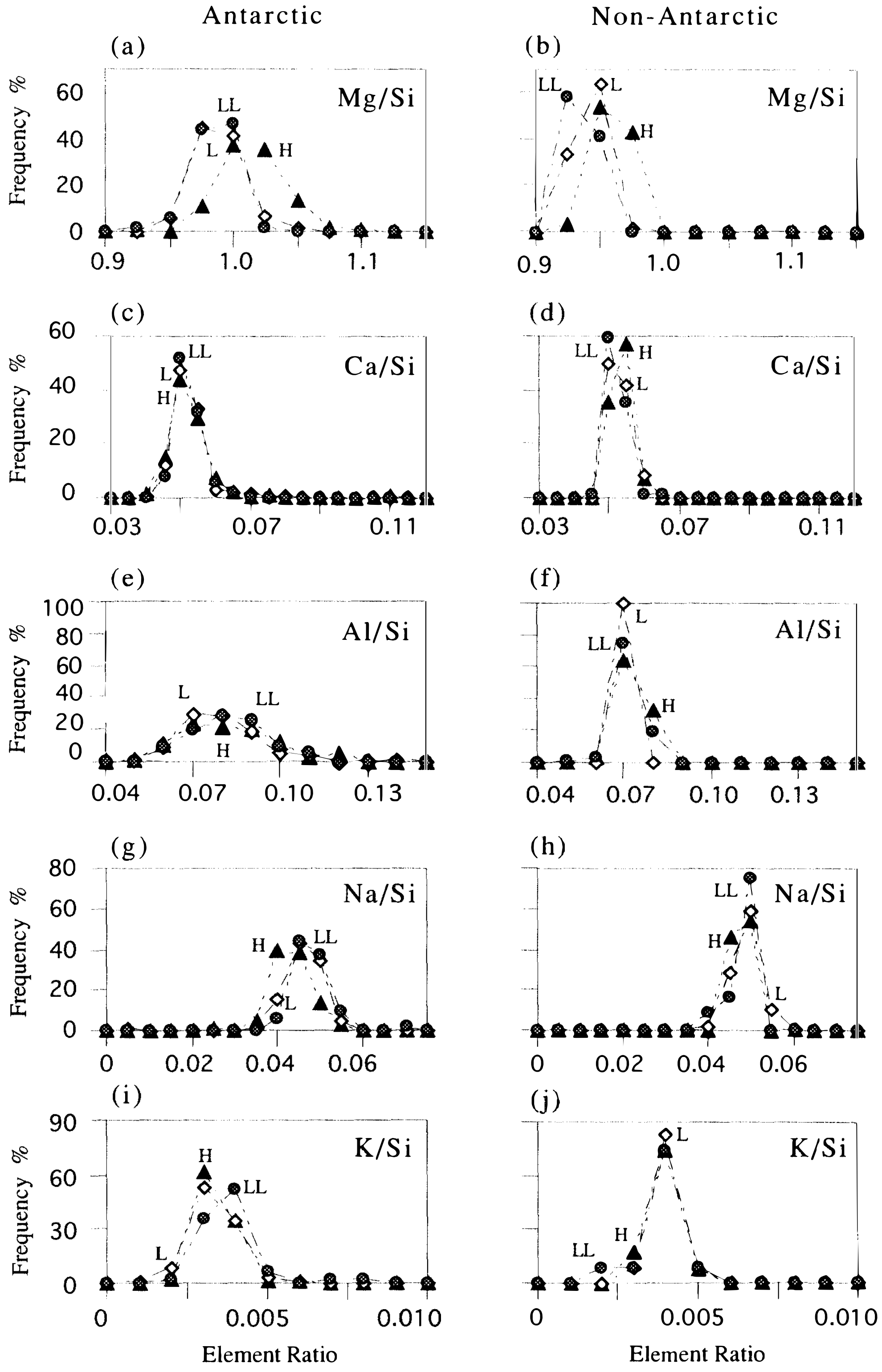


Fig. 7. Frequency (%) of Si-normalized major elements (in atomic) for Antarctic chondrites (left figures) including chondrites listed in Appendix (revised classification is adopted) and for non-Antarctic falls (right figures) by Jarosewich *(1990) except for chondrites with high Fe_2O_3 contents.*

Table 2. Interlaboratory difference in chemical composition between YANAI *and* KOJIMA *(1995) and* JAROSEWICH *(1990).*

	YANAI and KOJIMA (1995)			JAROSEWICH (1990)			YANAI and KOJIMA/JAROSEWICH		
	H (2)	L (4)	LL (2)	H (2)	L (4)	LL (2)	H (2)	L (4)	LL (2)
SiO_2	35.07	37.76	39.60	35.67	38.77	40.75	0.98	0.97	0.97
TiO_2	0.11	0.10	0.09	0.11	0.12	0.13	1.00	0.83	0.69
Al_2O_3	2.31	2.86	2.44	2.21	2.30	2.28	1.05	1.24	1.07
Cr_2O_3	0.48	0.49	0.54	0.43	0.52	0.53	1.12	0.94	1.02
Fe_2O_3*	7.11	1.10	0.00	6.32			1.13		
FeO	10.95	15.93	16.76	10.46	17.36	16.39	1.05	0.92	1.02
MnO	0.28	0.36	0.36	0.30	0.32	0.35	0.93	1.13	1.03
MgO	23.04	24.87	25.92	22.36	24.09	24.50	1.03	1.03	1.06
CaO	1.63	1.66	1.82	1.75	1.76	1.99	0.93	0.94	0.91
Na_2O	0.82	0.77	0.97	0.96	0.80	0.87	0.85	0.96	1.11
K_2O	0.09	0.09	0.11	0.11	0.09	0.10	0.82	1.00	1.10
P_2O_5	0.21	0.12	0.19	0.26	0.22	0.19	0.81	0.55	1.00
H_2O (+)	1.80	1.29	0.65	1.68	1.59	0.82	1.07	0.81	0.79
H_2O (−)	0.50	0.32	0.12	0.52	0.48	0.29	0.96	0.67	0.41
Fe (m)	9.22	4.67	2.99	9.48	4.38	2.93	0.97	1.07	1.02
Ni	1.40	1.13	0.90	1.69	1.18	1.00	0.83	0.96	0.90
Co	0.05	0.04	0.03	0.08	0.06	0.06	0.63	0.67	0.50
FeS	4.82	6.61	6.34	4.69	5.51	6.06	1.03	1.20	1.05
Total	99.89	100.15	99.81	99.04	99.54	99.22			
Fe (t)	25.77	22.01	20.04	25.00	21.36	19.52	1.03	1.03	1.03

Fe (m) and Fe (t) mean metallic Fe and total Fe, respectively.

Total numbers of chondrites are shown in parenthesis.

*Data of ALH-768 with higher Fe_2O_3 in YANAI and KOJIMA (1995) was selected.

Fe_2O_3 data are not given for most L and LL chondrites in JAROSEWICH (1990), and we regard the Fe_2O_3 as zero.

ference among chemical groups supports the conclusion obtained by KALLEMEYN *et al.* (1989) that the Na_2O contents of Antarctic L and LL chondrites are higher by about 7% than those of Antarctic H chondrites. Figure 7i and j show K/Si ratios of Antarctic chondrites and non-Antarctic falls. Some LL chondrites have high K/Si ratios (>0.006), and they (Y-74442 and Y-790527) are breccias including high-K clasts (IKEDA, 1983). Their high K contents is indigenous. The frequency diagrams of Fig. 7 indicate that Antarctic ordinary chondrites vary more widely than non-Antarctic falls. This reason is not clear, but may be sampling effects.

8. Summary

Most of the Fe_2O_3 in Antarctic ordinary chondrites were formed from metallic iron during terrestrial weathering. Kamacites in Antarctic chondrites were altered to limonites, but alteration of taenites was negligible. The water contents in Antarctic ordinary chondrites were mostly added to Antarctic meteorites as limonites with an average molar ratio of $Fe_2O_3/H_2O = 1/2–1/2.5$. There is no correlation between Fe_2O_3 of Antarctic chondrites and their weathering index. Most of the major elements except for metallic Fe are not affected by the weathering process except for the dilution effect. Therefore, we conclude that the Antarctic chondrites have experienced terrestrial weathering in a quasi-closed system to produce limonites insofar as the compositions of major elements are concerned.

The Mg/Si ratios seem to be the highest for H chondrites. The Na/Si ratios of H chondrites seem to be slightly lower on average than those of L and LL chondrites. The high K contents of the LL breccias (Y-74442 and Y-790527) are their original character before terrestrial alteration.

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Appendix. Revision of Classification for Some Antarctic Ordinary Chondrites

As already stated in Section 3, classification of Antarctic ordinary chondrites are examined using a UC diagram. Figure 4 indicates that some Antarctic chondrites plot in "wrong chemical groups" (Fig 4). For example, some equilibrated LL chondrites including olivine with a fayalite range of 26–31 mol% plot in the L chondrite range (Fig. 4). We call them "chondrites with unusual iron contents" in this paper and tabulated them in Table A1.

Among the Antarctic chondrites listed in Table A1, Y-793408 (L3) has a higher total Fe/Si ratio than the normal L chondrites. Microscopic observation of Y-793408 shows that most of the chondrules are smaller than 0.2 mm. Considering that the average chondrule sizes are 0.3–0.9 mm for ordinary chondrites and 0.2–0.4 mm for CO chondrites ("Meteorite News" compiled by Kojima and Yanai, 1996), Y-793408 could be a CO chondrite. However, taking it into consideration that the fine-grained matrices are 10–15 vol% for ordinary chondrites and 30–40 vol% for CO chondrites, the matrix of Y-793408 is 5–10 vol%, suggesting that it is an ordinary chondrite. Therefore, we tentatively classify it as an unusual chondrite. Y-792947 (H3) and Y-82038 (H3) chondrites are very similar in texture and chondrule size to Y-793408, suggesting that they also are unusual chondrites.

ALH-77015 (L3) has a normal petrographic appearance under the microscope but has a matrix similar in chemical composition to that of carbonaceous chondrites (Ikeda *et al.*, 1981), and thus we classify it as an unusual L3. Y-82133 (H3) has a low total Fe/Si ratio (0.699) and a high Fe^{2+}/Si ratio (0.352) in comparison to those of normal H chondrites (0.488 and 0.153, respectively, Table 1), and may be an L3 chondrite. Y-791835 (L3) has a high Fe^{2+}/Si ratio, and may be an LL3 chondrite. ALH-

Table A1. Antarctic chondrites with unusual iron contents and their revision.

Previous classification		Fe(t)/Si	Fe^{2+}/Si	Comments	Revision
		(in atomic)			
Y-74160	LL7	0.371	0.362	breccia, low metal	LL breccia with unusual total Fe
Y-74640	H6	0.874	0.427	high FeO	H6 with unusual FeO
Y-74660	LL3	0.531	0.318		LL3 with unusual FeO
Y-75028	H3	0.772	0.398	breccia	H3 breccia with unusual FeO
Y-75258	LL6	0.614	0.548	breccia, high FeO and low metal	LL breccia with unusual FeO
ALH-77015	L3	0.585	0.486	carbonaceous matrix	unusual L3
ALH-78015	LL3	0.614	0.234	low FeO	L3
Y-790521	LL	0.564	0.338	breccia	LL breccia with unusual Fe
Y-790527	LL5	0.549	0.304	breccia	LL breccia with unusual Fe
Y-790528	LL6, LL*	0.604	0.339	breccia	LL breccia with unusual Fe
Y-790530	LL5	0.569	0.292	breccia	LL breccia with unusual Fe
Y-790734	L6	0.778	0.288	shocked, large troilite grains	L6 with unusual metallic Fe
Y-790752	LL6	0.651	0.408	breccia	LL breccia with unusual Fe
Y-790782	LL6, LL*	0.566	0.311	breccia	LL breccia with unusual Fe
Y-790784	LL6 (An)	0.845	0.404	polymict breccia, high total Fe	LL breccial
Y-791413	L6	0.775	0.348	high total Fe	L6 with unusual total Fe
Y-791563	H4	1.093	0.148	limonite veins, high metallic Fe	H4 with unusual metallic Fe
Y-791634	L4	0.796	0.295	shocked	L4 with unusual metallic Fe
Y-791835	L3	0.567	0.397		LL3
Y-792947	H3	0.827	0.411	small chondrule size	unusual chondrite
Y-793284	H4	0.803	0.348	high Feo	H4 with unusual FeO
Y-793408	L3	0.781	0.428	small chondrule size	unusual chondrite
Y-793447	L4	0.686	0.246	high metallic Fe	L4 with unusual metallic Fe
Y-793506	LL6	0.627	0.386	breccia	LL breccia with unusual Fe
Y-793567	L3	0.802	0.366	high total Fe	L3 with unusual total Fe
Y-82038	H3	0.764	0.503	small chondrule size	unusual chondrite
Y-82133	H3	0.698	0.352	low total Fe	L3
Y-8410	LL5	0.602	0.356	high Fe	L5
A-881725	LL6	0.756	0.415		CK

Fe (t) means total Fe.
Previous classifications of chondrites are quoted from Yanai and Kojima (1995).
*Classification corrected by Kojima and Yanai (1996, with Errata).

78015(LL3) has a lower Fe^{2+}/Si ratio than the normal LL chondrites, and thus it may be an L3 chondrite. Y-8410(LL5) looks like an L5 under the microscope, has a higher total Fe/Si ratio than normal LL chondrites, and thus classified as an L5. A-881725(LL6) has a high total Fe/Si ratio in comparison to the normal LL chondrites, and a large amount of magnetites occurs in this chondrite. In addition, A-881725 has a low Na/Si ratio (0.02) in comparison to those of the normal LL chondrites (0.39, Table 1). These features indicate that A-881725 is a CK chondrite.

Y-74160 (LL7) is a breccia and has abnormally low total Fe; metallic Fe content is 0% and FeS is 0.34 wt%. Loss of the metal and sulfides might have happened during the sample preparation for chemical analysis. We classified Y-74160 tentatively as an LL breccia with unusual total Fe. Y-74640 (H6) has high FeO (17.26 wt%) in comparison to the normal H chondrites (about 10 wt%, Table 1), although the total Fe is comparable to those of the normal H chondrites. We classify it as an H6 with unusual FeO. Y-74660 (LL3) has low FeO (14.65 wt%) in comparison to the normal LL chondrites (about 19 wt%, Table 1), although it has total Fe comparable to the normal LL chondrites. It looks like a normal LL3 under the microscope, and is classified as an LL3 with unusual FeO contents. Y-75028 (H3) is a breccia and has high FeO (17.43 wt%) in comparison to the normal H chondrites, and we classified it as an H3 breccia with unusual FeO. Y-75258 (LL6) is a breccia and has extremely high FeO (25.38 wt%) in comparison to the normal LL chondrites, and is classified as an LL breccia with unusual FeO. Y-790734 (L6) and Y-791634 (L4) are heavily-shocked chondrites, and they have high metallic Fe (10.25 and 11.81 wt%, respectively) in comparison to the normal L chondrites (6.4 wt%, Table 1), classified here as L4 and L6 with unusual metallic Fe, respectively. Y-791413(L6) has high total Fe (25.97 wt%) in comparison to the normal L chondrites (about 22 wt%, Table 1), being an L6 with unusual total Fe. Y-791563 (H4) is a heavily weathered chondrite including limonite veins abundantly, has extremely high metallic Fe (metallic Fe, Fe_2O_3, FeO, and FeS are 17.91, 6.85, 5.59, and 7.93 wt%, respectively) in comparison to the normal H chondrites (metallic Fe, FeO, FeS are 13.6, 10, 6 wt%, respectively, Table 1), and thus is classified as an H4 with unusual metallic Fe. Y-793284 (H4) has slightly high FeO (14.01 wt%), and thus is classified as an H4 with unusual FeO. Y-793447 (L4) has slightly high metallic Fe (metallic Fe and Fe_2O_3 are 8.29 and 4.1 wt%, respectively), and thus is classified as an L4 with unusual metallic Fe. Y-793567 (L3) has high total Fe (25.96 wt%) in comparison to the normal L chondrites and is an L3 with unusual total Fe.

The other chondrites listed in Table A1, Y-790521 (LL), Y-790527 (LL5), Y-790528 (LL), Y-790530 (LL5), Y-790752 (LL6), Y-790782 (LL), Y-790784 (LL6), and Y-793506 (LL6) are breccia similar to one another, and have slightly high metallic Fe (or Fe_2O_3), high FeS, and/or low FeO. We classified them as LL breccias with unusual Fe.

The metallic Ni wt% of two chondrites (Y-790448, LL3, Ni=0.13 wt%, NiO=0.98 wt%; Y-791034, L5–6, Ni=0.44 wt%, NiO=0.77 wt%) are very low in comparison to other chondrites, as shown in Fig. 5b. The metallic Ni contents are not true, because there are several typographical errors in the table of chemical compositions of Antarctic meteorites in YANAI and KOJIMA (1995). For an example, the NiO and Ni contents should be interchanged for the two chondrites (Y-790448 and Y-791034), and the true contents of metallic Ni are 0.98 wt% for Y-790448 and 0.77 wt% for Y-791034, which are comparable to those of other chondrites. The Na_2O content of one chondrite (Y-793465, L6, Na_2O=0.1 wt%) is abnormally low (Fig. 5f), and this also is a typographical error; the true content is 1.0 wt%, comparable to other L chondrites. The Na_2O content of another chondrite (Y-791315, L4, Na_2O=0.43 wt%) seem to be slightly low in comparison to other H chondrites (Fig. 5f), and this chondrite includes clasts of H3 chondrite (YANAI and KOJIMA, 1995), suggesting a possibility of low-Na inclusions. The Na_2O content of one chondrite (Y-793214, LL5, Na_2O=1.39 wt%) is high in comparison to other L chondrites (Fig. 5f), although the reason is not clear.