

Boron and chlorine abundances in Antarctic chondrites: A PGA study

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Abstract: Boron and chlorine abundances were determined by prompt gamma-ray analysis for Antarctic meteorites of 22 carbonaceous chondrites and 12 ordinary chondrites. Both B and Cl contents of most Antarctic meteorites analyzed in this study are systematically higher than those for non-Antarctic chondrites of corresponding groups, implying that Antarctic meteorites of carbonaceous and ordinary chondrite groups were contaminated with not only Cl (and other halogens like I) but also B. Boron and Cl contents are correlated with each other in Antarctic ordinary chondrites whereas no apparent correlation can be seen for carbonaceous chondrites. Considering that interior portions were used for carbonaceous chondrites while interior and outer portions were randomly sampled for ordinary chondrite used in this study, B and Cl are distributed differently between the two groups of chondrite, suggesting that B and Cl independently behaved following their own chemical properties after contaminant(s) carrying these elements adhered on the surface of meteorites. Sea mist is a probable candidate for such a contaminant. Leaching experiments showed that no B is essentially recovered by water and acetone even from pulverized specimens, from which a fairly large fraction of Cl is recovered, confirming that B and Cl reside independently in chondrite samples and further that both elements behaved differently after sticking to these samples on Antarctica.

key words: boron, chlorine, Antarctic chondrite, terrestrial contamination, prompt gamma-ray analysis

1. Introduction

The solar system abundance of boron (B), together with those for Li and Be, is remarkably small compared with those of neighboring elements, He and C (Anders and Grevesse, 1989). Exact abundances of their solar system abundances are very important for refining a model of nucleosynthesis in stars and modeling of stellar evolutions (e.g., Cameron, 1973). Boron is cosmochemically classified as a moderately volatile element along with S and Cl and its abundance is informative in consideration of accretion processes for chondritic meteorites and thermal activities for differentiated meteorites.

Typical contents of B of chondritic meteorites are about 1 ppm (Wasson and Kallemeyn, 1988), which is considerably lower than B contents of terrestrial igneous rocks. As there are few analytical methods applicable for such low abundances of B in rock samples, the number of reported values for B is very limited compared with those

for other similarly volatile elements. Prompt gamma-ray analysis (hereafter, PGA) must be the most advantageous analytical method for B in rock samples. As prompt gamma-rays are used in PGA, it is applicable to such elements as B which emits no decay gamma-rays after capturing neutrons. In fact, B is one of elements having the highest analytical sensitivity in PGA.

Curtis *et al.* (1980) determined B in non-Antarctic chondrite samples (all observed falls) by using PGA and compared analytical results between fresh samples dug from the interior and samples having no handling records after their recoveries. They found a systematic difference between the two groups, with samples with unknown history having systematically higher values than those for interior-derived samples. Such a systematic difference seems to be much apparent in carbonaceous chondrites; most interior samples of carbonaceous chondrites have B contents of 1 ppm or less, whereas some samples with unknown history have enormously high contents reaching to 100 ppm. Curtis *et al.* (1980) regarded such high contents as the result of contamination of B due to careless handling and storage after falling of meteorites on the earth.

Using PGA method, Curtis and Gladney (1985), Shaw *et al.* (1988) and Zhai and Shaw (1994) reported B contents for 64 meteorites of CI, CM, CV, CO, E, L and LL groups. As they used mostly interior samples of these meteorites, their values seem to be reliable. Average B contents for these meteorite groups are smaller than 1 ppm and an average value of CI chondrite (0.77 ppm) is 35% smaller than the estimated value (1.2 ppm) by Wasson and Kallemeyn (1988). In order to deepen our cosmochemical knowledge of B, it is basically needed to have more data of reliable B contents in meteorite sample of both primitive and differentiated groups.

As B is a typical, contamination-prone element, the selection of samples is essential for obtaining reliable and indigenous value of B. Considering that the contamination of B mainly occurs during storage and handling of meteorites at museums and/or laboratories, Antarctic meteorites seem to be promising specimens for the determination of B because Antarctic meteorites had been locked in ice on Antarctica for long time and have been kept stored in clean storage facilities under strict control after their collection on Antarctica. It is, however, well acknowledged that Antarctic meteorites have suffered elemental contaminations on Antarctica. In fact, chlorine (Cl) and iodine (I) were found to be anomalously enriched at the surface and the outer part of Antarctic meteorites, suggesting that some contaminants containing halogens were added to the surface of meteorites on Antarctica (*e.g.*, Dreibus and Wänke, 1983; Dreibus *et al.*, 1986; Ebihara *et al.*, 1990; Langenauer and Krähenbühl, 1993). Then, a question may arise: is B also influenced by such a contaminant? If not, Antarctic meteorites can be very useful specimens for cosmochemical study of B. When it is the case, can it be removed by any technique? If yes for the second question, Antarctic meteorites can still serve for our cosmochemical study of B.

This study was initiated in order to answer these questions. In this study, B was determined by PGA along with Cl. Both elements can be determined non-destructively by PGA with high sensitivities. In addition to these elements, S was also targeted for its determination, considering that these three elements have similar condensation temperatures. Analysis was done for bulky specimens without any treatment for most cases. Some samples were leached with acetone and water to see whether any solvent

is effective in removing contaminant(s) if any.

2. Experimental

2.1. Samples

We have analyzed B and Cl for 22 carbonaceous chondrites and 12 ordinary chondrites. 22 carbonaceous chondrites include 3 CMs, 5 COs, 1 CV, 10 CK, 2 CR and 1 CH. Ordinary chondrites are grouped into 3 Ls, 1 LL, 7 Hs and 1 R. These meteorite samples were loaned by the National Institute of Polar Research (NIPR) and the National Aeronautics and Space Administration (NASA); interior portions were allocated for carbonaceous chondrites while both interior and outer portions were randomly allotted for ordinary chondrites. Meteorite names with classification groups and sample weights used for analysis are listed in Tables 1 and 2 for carbonaceous and ordinary chondrites, respectively.

2.2. PGA

Either lump or powder samples weighing 0.1 to 1 g were used for PGA. If needed, some lump specimens were further pulverized. For several samples, their aliquants had been already analyzed for halogens by radiochemical NAA and found to have anomalously high abundances of chlorine and iodine compared with their normal contents in non-Antarctic fall meteorites (Shinonaga *et al.*, 1994). Samples were heat-sealed in fluorinated ethylene-propylene (FEP) film bags and were measured by using the PGA system installed at the JRR-3M reactor of Japan Atomic Energy Research Institute (JAERI). Both cold and thermal neutrons guided out from the reactor were used for analysis. Samples were irradiated by neutrons for 1 to 3 h and prompt gamma rays emitted were simultaneously measured with a Ge detector surrounded with BGO Compton suppressor. The experimental details of PGA were already described elsewhere (Oura *et al.*, 2002).

2.3. Leaching experiment

Using three meteorite samples having high B and Cl contents (Yamato (Y) 791428,81, Y790461,95 and Allan Hills (ALH) 77011,85), leaching experiments were conducted. Although no information is available for chemical species of contaminants for B and Cl, water and acetone were chosen for trying to dissolve some inorganic and organic species, respectively. After PGA for their bulk analyses, samples were soaked in 5 ml of water for 1 day with occasional stirring. After centrifugation, residual samples were soaked in 5 ml acetone for 1 day. The residual samples were further treated with 5 ml water for 1 day with occasional ultrasonic agitation. The final residues were analyzed for B and Cl by PGA. Some additional descriptions are given in the later Section 3.3.

3. Results and discussion

3.1. Boron and chlorine contents of Antarctic carbonaceous chondrites

PGA data for B and Cl in Antarctic carbonaceous chondrites are summarized in

Table 1, where data are arranged in accordance of chondritic groups. Sample weights used for analyses also are shown. It is known that CI and CM chondrites have exceptionally high contents of H, most of which is present as water and OH groups in hydrous minerals, reaching up to 2 wt%. Such a high abundance of H may influence the accuracy of data in PGA, considering that H can enhance the analytical sensitivity due to the effective scattering of neutrons. Mackey *et al.* (1991) examined the effect of H on the sensitivity of B in disk shaped-samples of SRM 1571 orchard leaves (H content: 5.84%) and obtained a sensitivity enhancement factor of B of 1.80% enhancement/% H (w/w). Considering the H content range of CM chondrites (less than 1.6 %) and the size of meteorite samples used in this study (less than 1 g), the effect on elemental sensitivities due to neutron scattering must be too small to be compared with analytical errors accompanied by PGA data shown in Table 1 and, hence, can be neglected.

According to Wasson and Kallemeyn (1988), average Cl contents of CM, CO and CV are 160, 240, 210 ppm, respectively. It is interesting to note that Cl contents of CMs are somewhat lower than those for COs and CVs. Apparently, most Cl contents of Antarctic carbonaceous chondrites analyzed in this study are systematically higher than average values for non-Antarctic carbonaceous chondrites of corresponding

Table 1. PGA data for Cl and B abundances in Antarctic carbonaceous chondrites.

Meteorite	Type	Weight [g]	Cl [ppm]*	B [ppm]*
LEW90500,25	CM2	0.4041	461±69	0.566±0.192
Y791198,77	CM2	0.3798	89±48	1.39±0.20
Y793321,67	CM2	0.4509	732±13	0.839±0.068
ALH77003,86	CO3	0.5940	273±37	0.781±0.51
Y791717,88	CO3	0.2249	378±12	1.64±0.09
Y81020,73	CO3	0.3850	399±11	1.12±0.08
Y82050,74	CO3	0.3996	769±14	2.13±0.08
Y82094,90	CO3	0.9371	417±7	0.154±0.027
Y86751.56	CV3	0.5439	385±39	1.13±0.16
ALH85002,32	CK4	0.2779	227±57	0.48±0.24
DAV92300,14	CK4	0.4466	260±35	1.15±0.27
EET99430,13	CK4	0.5151	753±30	2.84±0.25
LEW86258,15	CK4	0.2432	183±39	1.45±0.32
PCA82500,41	CK4	0.6566	540±31	1.05±0.22
PCA91470,13	CK4	0.5699	295±19	0.75±0.16
EET83311,14	CK5	0.1679	313±28	1.38±0.31
EET87507,21	CK5	0.2342	412±34	1.42±0.31
EET87860,19	CK5-6	0.3217	296±51	0.78±0.21
LEW87009,20	CK6	0.2086	135±45	2.92±0.38
A881595,65	CR2	0.1798	1470±70	6.28±0.57
EET92042,24	CR2	0.1727	165±29	1.33±0.29
PAT91546,6	CH3	0.1576	94±31	0.23±0.35

*Errors accompanied are due to counting statistics (1 σ).

groups. Such overabundant Cl must be contributed by Cl-containing contaminant(s) on Antarctica, as well acknowledged (*e.g.*, Dreibus and Wänke, 1983; Dreibus *et al.*, 1986; Ebihara *et al.*, 1990; Langenauer and Krähenbühl, 1993). In the meanwhile, average B contents in interior portions of non-Antarctic CM, CO and CV chondrites are 0.60 (0.27–1.30), 0.46 (0.44–0.49) and 0.43 (0.33–0.56) ppm, respectively (values in parentheses are concentration ranges in ppm) (Curtis and Gladney, 1985; Shaw *et al.*, 1988; Zhai and Shaw, 1994). Being different from the case for Cl, CM interiors have systematically higher values of B than those for CO and CV interiors. Boron contents of Antarctic CM chondrites are in the range for those of non-Antarctic interiors, while B contents of Antarctic COs are systematically above the corresponding range of non-Antarctic COs for most cases, just like for the case of Cl contents in Antarctic CMs, COs and CVs. For CK chondrites, 262 ppm and <0.2 ppm were obtained for Cl and B contents, respectively, for the interior part of the Kobe meteorite (Oura *et al.*, 2002). All Antarctic CKs analyzed in this study show systematically higher B contents than the upper limit value of Kobe. There appears no apparent correlation between weathering indices and contents of B and Cl in Antarctic CKs. Boron and Cl contents in a CR2 specimen, Asuka (A) 881595,65 are the highest among those for Antarctic carbonaceous chondrites analyzed in this study, being much higher compared with their average values of non-Antarctic carbonaceous chondrites.

Concentrations of B and Cl in Antarctic carbonaceous chondrites are compared in Fig. 1. A correlation coefficient between B and Cl contents can be calculated to be 0.72 for all samples listed in Table 1. This value decreases down to 0.23 when data for A881595 are excluded. Apparently, a higher correlation coefficient (0.72) is derived from exceptionally high contents in A881595, suggesting no apparent correlation between B and Cl contents for Antarctic carbonaceous chondrites. However, considering that B contents in Antarctic carbonaceous chondrites are systematically higher than non-Antarctic average values, it must be highly probable that carbonaceous meteorites have suffered contamination of B on Antarctica to some extent.

Sulfur is cosmochemically classified as a volatile element, as suggested by its 50% condensation temperature of 684 K (Fegley, 1993), which is somewhat comparable to but systematically lower than those for B (745 K) and Cl (863 K). Figure 2 shows a correlation of B/Si vs. S/Si for Antarctic carbonaceous chondrites (unpublished data for S contents, which will be reported elsewhere). In this figure, values for interior samples of non-Antarctic carbonaceous chondrites from literatures also are plotted by using open symbols. Volatile element abundances are known to be variable among groups of carbonaceous chondrites: CI chondrites have the highest contents and are followed by CM, CO-CV and CR chondrites with decreasing contents in this order. S/Si ratios obtained for Antarctic carbonaceous chondrites are consistent with those for corresponding non-Antarctic chondrites. CM values obtained in this study are in excellent agreement with non-Antarctic CM values. Antarctic CO and CV chondrites have similar S/Si values to those for non-Antarctic meteorites. Antarctic CK chondrites show a larger variation in S/Si ratios compared with those for other Antarctic carbonaceous groups, with small values overlapping with those for CO-CV chondrites. Such a large variation may reflect S loss caused by terrestrial weathering on Antarctica, as suggested by low abundances of S in severely weathered CK chondrites (Oura *et al.*,

2002).

An insert in Fig. 2 shows a correlation of B/Si vs. S/Si only for interior samples. CI, CM and CO-CV chondrites show discrete, individual S/Si ratios while their corresponding B/Si values are not similarly separable from group to group. CIs has the

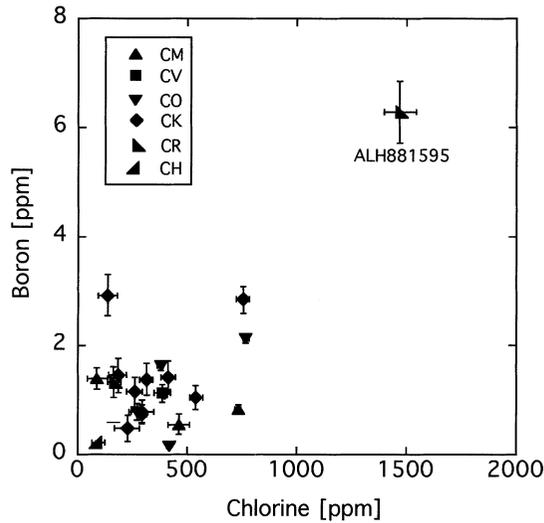


Fig. 1. Correlation between B and Cl contents of Antarctic carbonaceous chondrites analyzed in this study.

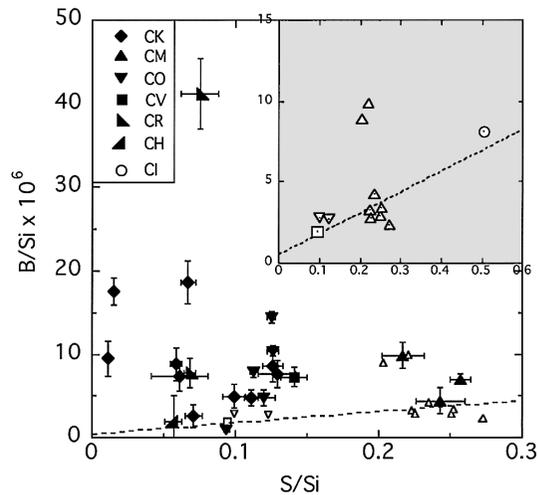


Fig. 2. Correlation between B/Si and S/Si ratios in carbonaceous chondrites. Literature values shown by open symbols for interior samples of non-Antarctic carbonaceous chondrites are also plotted together with our determinations shown by closed symbols. The insert is an extended representation (for x-axis) of literature values for interior samples only. A dashed line indicates a correlation line.

highest S/Si value and are followed by CMs and COs-CVs in the order. Without two anomalously high values for the Murray CM chondrites, whose Na contents are also anomalously low (50% lower than the CM average), B/Si ratios apparently correlate with S/Si ratios in non-Antarctic carbonaceous chondrite interiors, suggesting that B data derived from interior samples are cosmochemically meaningful. Although condensation temperatures of S and B are different by 70 degree, Si-normalized abundances of B and S decrease similarly from CIs to CVs, suggesting that these two elements behaved similarly as moderately volatile elements during accretion of carbonaceous chondrite parent bodies.

B/Si ratios obtained in this study, however, do not correlate with S/Si ratios, as clearly noticed in Fig. 2. Almost all of B/Si values for Antarctic carbonaceous chondrites are plotted above the correlation line shown by a dashed line in Fig. 2. Apparently, B is overabundant in those meteorite samples analyzed in this study. It may be pointed that B/Si ratios for Antarctic CRs are similar to or even higher than those for COs-CVs, which is opposite trend supposed to be seen in uncontaminated, fresh specimens such as interior portions of non-Antarctic fall samples. Some meteorites with extremely low S/Si ratios have reversely high B/Si ratios. This may be explained in terms of either contamination of B or weathering loss of S on Antarctica, or both of them. Although B and Cl are not apparently correlated with each other in Antarctic carbonaceous chondrites (Fig. 1), it may be premature to conclude that contaminants contributing to B and Cl contents of Antarctic carbonaceous meteorites are different. This will be discussed again later.

3.2. Boron and chlorine contents of Antarctic ordinary chondrites

Boron and Cl contents of Antarctic ordinary chondrites analyzed in this study are arranged by groups in Table 2. Average Cl contents in ordinary chondrites are estimated to be 80, 76 and 130 ppm for H, L and LL chondrites, respectively (Wasson and Kallemeyn, 1988) and average B contents in the interior portion of these groups are 0.51 (0.15–1.13), 0.65 (0.16–1.64) and 0.49 (0.44–0.56) ppm, respectively (values in parentheses are concentration ranges) (Curtis and Gladney, 1985; Shaw *et al.*, 1988; Zhai and Shaw, 1994). As is the case for carbonaceous chondrites, Cl contents in Antarctic ordinary chondrites analyzed are systematically higher than Cl averages in corresponding groups of non-Antarctic ordinary chondrites. Similarly, all B values obtained here are systematically larger than corresponding average values but half of them fall in the concentration ranges of individual groups.

Figure 3 shows a correlation between B and Cl contents in Antarctic ordinary chondrites obtained in this study. In contrast to the case for carbonaceous chondrites, there appears an apparent correlation between Cl and B contents in Antarctic ordinary chondrites. ALH77011,85 has an anomalously high Cl and B contents, which increase a correlation coefficient between B and Cl contents up to 0.90. If this sample is excluded, the value decreases to 0.44, which implies a weak correlation. However, the correlation coefficient is increased to 0.79 when data for LL and R chondrites are further excluded, for each of which only one set of data are available in this study.

An ellipse in Fig. 3 indicates a range of B and Cl contents for non-Antarctic ordinary chondrites from literatures; B and Cl range from 0.14 to 5.95 ppm and from 7

to 212 ppm, respectively. Being different from the case for Cl contents non-Antarctic ordinary chondrites suffer significant contamination of B, yielding a poor correlation coefficient of 0.02. An apparent, positive correlation between B and Cl contents in Antarctic ordinary chondrites (Fig. 3) suggests that these meteorites are contaminated with both B and Cl on Antarctica after their fall. It may be noted here that Antarctic carbonaceous chondrites have no apparent correlation between B and Cl contents as

Table 2. PGA data for Cl and B abundances in Antarctic ordinary chondrites.

Meteorite	Type	Weight [g]	Cl [ppm]*	B [ppm]*
Y791429,94	L3	0.2374	326±14	1.21±0.09
ALH77011,85	L3.5	0.0786	1950±30	2.73±0.14
ALH77252.71	L3/L6	0.3228	211±10	0.856±0.075
ALH77304,71	LL3	0.1858	282±13	1.36±0.08
Y790461,95	H3	0.2307	662±17	1.13±0.10
Y791428,81	H3	0.3476	703±18	1.34±0.08
Y74155,101	H4	0.3036	327±35	1.14±0.17
Y74155,102	H4	0.4353	298±27	0.93±0.13
Y74155,103	H4	0.5759	168±22	0.78±0.11
Y74014,102	H6	0.3555	294±30	1.00±0.15
Y74014,103	H6	0.2767	302±33	1.00±0.17
PCA91241,6	R3.8	0.2151	369±30	1.68±0.26

*Errors accompanied are due to counting statistics (1σ).

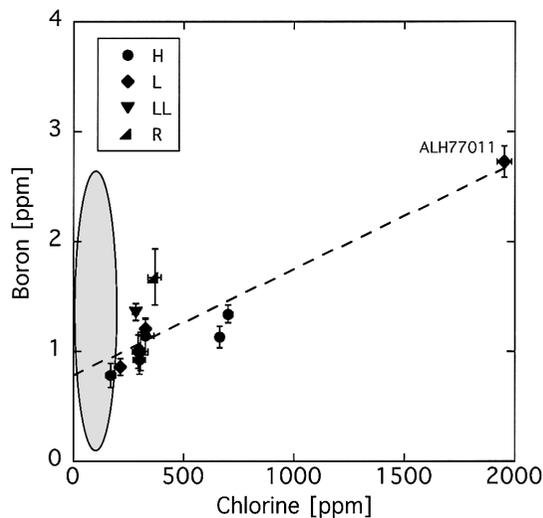


Fig. 3. Correlation between B and Cl contents of Antarctic ordinary chondrites. A dashed line is a fitted line for all values, showing a correlation coefficient of 0.90. An ellipse shows a range of B and Cl contents in non-Antarctic ordinary chondrites from literatures. Note that one data set is available each for LL and R chondrites.

discussed above. This is partly because the specimens of carbonaceous chondrites used in this study were mostly sampled from their interior portions. Further discussion will be done in the next section.

3.3. *Dissolution behaviors of B and Cl in Antarctic ordinary chondrites in chemical leaching*

As Antarctic ordinary chondrites were confirmed to be somewhat contaminated with B and Cl on Antarctica, leaching experiments were conducted so that any information concerning their contaminants could be derived. If contaminants could be separated by chemical leaching using appropriate solution(s), it would further promote the utility of Antarctic meteorites for cosmochemical studies. Considering their rather high contents of B (and Cl, accordingly), following three ordinary chondrites were chosen for leaching experiments; Y791428,81 (H3), Y790461,95 (H3) and ALH 77011,85 (L3). After PGA of untreated specimens, these three meteorites were processed differently as follows;

Y791428,81: A chip weighing 348 mg was successively leached by water for 1 day, acetone for 1 day and water for 1 day.

Y790461,95: A chip weighing 230 mg was successively leached with water and acetone in the same manner as that for Y79142. After the last leaching step, the residue was ground in an agate mortar. The same suit of leaching steps was applied to the powdered sample.

ALH 77011,85: Powdered sample weighing 76 mg was successively leached with water and acetone in the same manner as applied to Y791428,81 and Y790461,95.

The initial (untreated) samples and the residual samples were analyzed by PGA for B and Cl and their results are shown in Fig. 4, where dissolved and residual fractions of B and Cl are partitioned in individual rectangles. Values in parentheses shown below individual meteorite names indicate residual mass fractions (in%) after water-acetone leaching. For Y790461,95, data for chip and powdered samples are figured separately. For this meteorite, dissolved fractions of B and Cl and mass loss for the chip sample were not considered for the powdered sample.

For samples in chips (Y791428,81 and Y790461,95), essentially no mass loss was confirmed in leaching by water and acetone. With such leachings, B contents were not changed, while about 10% of Cl was leached for both samples. It is well acknowledged that some halogens in meteorites are leached by water to some extent (e.g., Reed and Allen, 1966; Kato *et al.*, 2000). In ordinary chondrites, halite and chlorapatite are major host phases for Cl. Halite can be easily dissolved in water, whereas chlorapatite cannot be dissolved; calcium phosphates including chlorapatite are known to be selectively leached by EDTA (ethylenediamine-tetraacetic acid) (Shima and Honda, 1967) and easily dissolved in mineral acids. Considering that the specimens of Y791428,81 and Y790461,95 used are chips, dissolved fractions of 10% for Cl seem to be a little too high to be explained in terms of selective dissolution of halite.

The powdered specimen of ALH 77011,85 reduced its mass by as much as 18% with leaching while only 4% mass loss was observed for the powdered Y790461,95. Considering that water attacks only minor minerals such as halite for ordinary chondrites, mass loss of 18% for ALH 77011,85 is too large to be explained in terms of

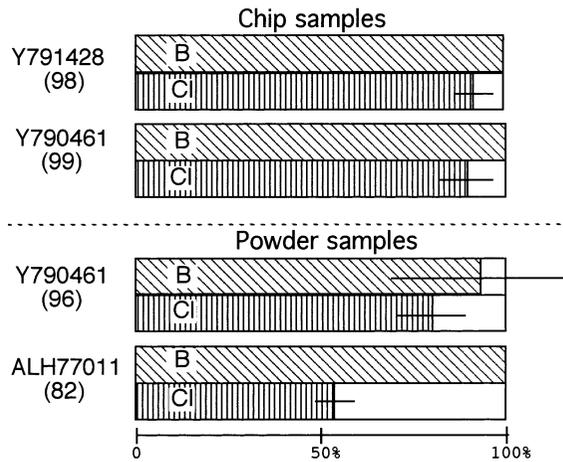


Fig. 4. Residual fractions of Cl and B (in%; shaded area) after water-acetone residues relative to their bulk contents. Horizontal bars indicate associated errors due to counting statistics in PGA (1σ). Numbers in parentheses below sample names are residual mass fractions in% relative to their initial masses.

selective dissolution of such indigenous mineral phases. For this meteorite, about half of Cl was removed after water/acetone leachings. Leached Cl must be largely contributed by terrestrial contaminants containing Cl in consideration of a high Cl content of bulk sample (1950 ppm; 25 times higher than the average value of the same group of chondrites). Buchwald and Clarke (1989) observed akaganeite (formulated as FeOOH) in Antarctic meteorites and explained its presence as a corroded product of Fe-Ni minerals with water on Antarctica. Akaganeite was reported to contain Cl of up to 5 wt%, presumably in the chemical form of FeCl_3 (Buchwald and Clarke, 1989). Thus, the 18% mass loss can be partly explained by dissolution of such weathering product(s) in addition to indigenous minor mineral(s) including halite. It must be probable for some additional mineral species be dissolved together. However, no noticeable changes in chemical composition were obtained by PGA except for B and Cl after leaching. Much smaller mass loss (4%), lower Cl content (662 ppm) and smaller dissolution loss of Cl (25%) are all consistent with each other for Y790461,95. Applying successive dissolution by several different solutions to an Antarctic H6 chondrite (Y74014), Kato *et al.* (2000) found that 48% of total Cl (753 ppm) was dissolved in water and that a secondly large fraction of Cl (28%) was recovered by acid leaching. Such acid-leached Cl must be mostly attributable to Cl-containing contaminants. The Cl remaining after water-acetone leachings for both ALH 77011,85 and Y790461,95 must also be derived from such contaminants to a large extent, although some contributions can be made by the dissolution of indigenous minerals such as chlorapatite.

Among the Antarctic ordinary chondrites analyzed in this study, ALH 77011,85 has the highest content of B (2.73 ppm), which is 4 times higher than the L chondrite average (0.65 ppm) for non-Antarctic interior samples. Although the ALH 77011,85 specimen used in the leaching experiment was in powder, which is to be efficient in

leaching as implied by a large recovery of Cl by water/acetone leaching, essentially no B was recovered by either water or acetone. Including this sample, B contents were observed to be unchanged within uncertainties of B data after leachings by water and acetone even for powdered specimens, which forms a striking contrast to the dissolution behavior of Cl. Thus, there appear a large difference in dissolution behaviors between Cl and B. Although fairly large errors are accompanied by B content data, it is apparent that B-containing contaminant(s) cannot be removed by acetone- and water-leaching.

In the previous section, it was confirmed that B and Cl contents are not correlated in Antarctic carbonaceous chondrites but that they are correlated in Antarctic ordinary chondrites. In spite of such difference, it was concluded that both B and Cl are overabundant not only in Antarctic ordinary chondrites but also in Antarctic carbonaceous chondrites, being caused by contaminant(s). For Cl (and some other halogens), airborne sea spray can be a candidate for such a contaminant (Kato *et al.*, 2000). Boron may be also delivered by such substances, considering a rather high content of B in sea water (4.5 mg/kg; Noakes and Hood, 1961). Anderson *et al.* (1994) found that atmospheric B originated from seawater, having higher abundance than that in particulates in warm areas and that gaseous B condensed onto atmospheric particulates (aerosols) during its transportation, especially at low temperature. B-containing aerosols thus produced must adhere to the surface of meteorites on Antarctica. It is also suggested that atmospheric B condense onto the surface of meteorites. Such aerosols could also contain Cl (and other halogens), with B and Cl being contaminating the surface of meteorites at the same time. If aerosol would be a contaminant for B and Cl, the degree of their overabundances in meteorites (especially, on the surface of meteorites) can be correlated with the duration of meteorites on bare ice fields of Antarctica, but probably not with the duration of meteorites stored in the ice. With the present data from this study and literatures, it is premature to discuss the correlation of B and Cl contents and terrestrial ages, because of no way to separate two stages of durations and very little data of terrestrial ages.

After adhering to the surface, Cl and B behaved differently, following their chemical properties during weathering on Antarctica. Probably, Cl is transported relatively into the deep portion through cracks, possibly in the form of Cl^- and forms FeCl_3 to react with Fe-Ni alloys in ordinary chondrites or carbonaceous chondrites having metal phases. In the meanwhile, B, which is originally in the form of borate in the sea and probably in the sea mist, stays at the surface or in the shallow layer and is fixed in acid-insoluble compound(s). In this study, interior portions were used for carbonaceous chondrites whereas both interior and outer portions were sampled for ordinary chondrites. This may explain the difference in correlation of B and Cl contents between carbonaceous and ordinary chondrites. If whole meteorite specimens had been used, B and Cl contents would be positively correlated in Antarctic meteorites regardless of types.

4. Conclusion

- 1) Most Cl contents of Antarctic carbonaceous chondrites analyzed in this study

are systematically higher than average values for non-Antarctic carbonaceous chondrites of corresponding groups. Boron contents of Antarctic CM chondrites are in the range for those of non-Antarctic CM interiors, while B contents of Antarctic COs are systematically above the corresponding range of non-Antarctic COs for most case, just like for the case of Cl contents in Antarctic CMs, COs and CVs. With in a limited number of B data for CK and CR chondrites, Antarctic chondrites of these groups analyzed in this study show systematically higher contents compared with average B contents of non-Antarctic carbonaceous chondrites. However, no apparent correlation can be seen between B and Cl contents for Antarctic carbonaceous chondrites.

2) Boron and S contents (or their Si-normalized abundances, to be more suitable) are correlated with each other in non-Antarctic carbonaceous chondrites, as suggested by the similarity in their condensation temperatures. B/Si ratios do not correlate with S/Si ratios for Antarctic carbonaceous chondrites analyzed in this work, with almost all of B/Si values for Antarctic carbonaceous chondrites being plotted above the correlation line defined by non-Antarctic carbonaceous chondrite interiors. This clearly suggests that Antarctic carbonaceous chondrites are contaminated with B.

3) Chlorine contents of Antarctic ordinary chondrites analyzed in this work are systematically higher than Cl averages in corresponding groups of non-Antarctic ordinary chondrites. Similarly, all B values obtained here are systematically larger than corresponding average values but half of them fall in the concentration ranges of individual groups. In contrast to the case for carbonaceous chondrites, there appears an apparent correlation between Cl and B contents in Antarctic ordinary chondrites, suggesting that these meteorites have gotten contaminated with both B and Cl on Antarctica after their fall.

4) The powdered ALH 77011,85 specimen reduced its mass by as much as 18% with water and acetone leachings, with its Cl being leached by half. Selective dissolution of some indigenous mineral(s) such as halite and weathered product(s) such as akaganeite can explain such a large mass loss considering that this meteorite specimen used in this study contains the highest Cl content (1950 ppm). In spite of its highest content of B (2.73 ppm), ALH 77011,85 showed no loss of B upon being leached with water and acetone. These evidences imply that B and Cl reside in different mineral phase(s) of the sample although these elements were largely embedded in the meteorite after its fall on Antarctica. Boron and Cl were introduced into the meteorite by either a common contaminant or different individual contaminants. If the former is the case, which seems to be more plausible, B and Cl adhered on the surface of meteorites and were diffused to different phases according to chemical properties of B and Cl. In this case, B and Cl must have originated from the sea and been transported to inland of the Antarctica in a form of volatile chemical compound.

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