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Chemical composition of Yamato (Y) 000593 and Y000749: Neutron-induced prompt gamma-ray analysis study

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Abstract: Neutron-induced prompt gamma-ray analysis (PGA) was applied to Antarctic nakhlites, Yamato (Y) 000593 and Y000749 together with Nakhla for the non-destructive determination of most major and minor elements (plus some trace elements). In addition to analyses of lump samples of these three meteorite, powder samples representing six different portions within Y000593 also were analyzed for discussing the chemical heterogeneity. As a result, it was confirmed that most major elements are homogeneously distributed among Y000593 within an error of ±10%. Chemical compositions of Y000593 and Y000749 are essentially identical within error limits, supporting the suggestion that these meteorites are paired. Compositional similarity is also confirmed between Nakhla and Y000593 (and Y000749), verifying that Y000593 (and Y000749) belong to nakhlites. Based on our PGA data coupled with literature data for Martian meteorites, we propose a diagram used for classifying achondrites and further for grouping into individual groups of Martian meteorites. Although there are some scatterings in B and Cl data, we would propose their abundances in nakhlites to be 3.33 ppm and 80 ppm, respectively. Our H data are systematically higher than their literature data. Although further refinements in our analytical procedure of PGA are required for getting more reliable and accurate values of H in Martian meteorites, it is suspected that some literature values of H contents in Martian meteorites are a little too small.

key words: Y000593, Y000749, prompt gamma-ray analysis (PGA), chemical composition, hydrogen

1. Introduction

Yamato (Y) 000593 and Y000749 (Kojima and Imae, 2001) were recovered from the bare ice field near the Yamato Mountains. These meteorites were suggested to be paired based on the filed recognition and petrographic features (Kojima *et al.*, 2002) and were inferred to be classified as nakhlites based on petrographical observations and noble gas analyses (Imae *et al.*, 2002). So far about 40 meteorites are grouped into Martian meteorites (shergottites, nakhlites, Chassigny and ALH84001). Y000593 and Y000749 are among the latest meteorites belonging to Martian meteorites accessible to us. Among Martian meteorites, shergottites are predominant in number of specimens. Nakhlites are relatively rare, to which eight meteorites including Y000593 and Y000749 belong. The discovery of Y000593 is significant in two issues; it is the largest nakhlite (weighing 13.7 kg) and it is the first nakhlite recovered on Antarctica. The latter issue implies that unique meteorites will be being discovered on Antarctica by future expeditions, which eventually extend our understanding of the solar system. The former issue seconds this perspective; a large specimen allows us to investigate the sample from different scientific viewpoints using different observational techniques.

In this study, neutron-induced prompt gamma-ray analysis (hereafter, PGA) was applied to Y000593 and Y000749 for determining their chemical compositions. Comparing to conventional instrumental neutron activation analysis or other elemental analysis methods, PGA has several advantages as a bulk chemical analysis method; it can non-destructively determine Si and S in addition to other major elements (Latif *et al.*, 1999), it can be applied to any size and any shape of samples (Nakahara *et al.*, 2000) and so on. Besides Y000593 and Y000749, Nakhla was additionally analyzed for comparison. For Y000593 and Nakhla, both lump and powder samples were analyzed whereas only lump sample was subjected to PGA for Y000749. From these analyses, we describe the chemical characteristics of these meteorites. As Y000593 and Y000749 were suggested to be paired nakhlites, we aim to judge whether such suggestions are seconded from elemental compositions. For Y000593, six sub-samples were prepared by taking from different geometric positions, and were separately analyzed by PGA. By comparing their data, we discuss how homogeneously or heterogeneously elements are present in Y000593. Finally, compositional characteristics of selected elements in Antarctic nakhlites are discussed in comparison with those of Nakhla.

2. Experimental

2.1 *Sample*

Three meteorites were analyzed by PGA in this study; Y000593, Y000749 and Nakhla. Lump samples of these three meteorites (Y000593,66, Y000749,46 and Nakhla,55) were analyzed by using internal mono-standard method (Sueki *et al.*, 1996). The specimens of Y000593,66 and Y000749,46 were loaned from NIPR only for the PGA. The specimen Nakhla,55 was sampled from the interior of a large mass (preserved at the British Museum) at the lunar sample processing room at the Johnson Space Center, NASA. The specimen had been kept sealed in an aluminum container filled with inert gas and was sealed into a FEP (fluorinated ethylene propylene) bag just before the experimental run of PGA. For Y000593, powder samples were prepared at NIPR. When breaking a main mass of Y000593, lump specimens (Y000593,40 through Y000593,45,) were sampled from six different positions which are geometrically remote to each other. Lump samples weighing about 2 to 3 g collected from six sites were carefully ground in clean agate mortars. A part of each powdered sample weighing about 0.1 g was also subjected to the PGA. At the same time, the powdered Nakhla sample was prepared at our laboratory in the same manner as taken for Y000593 powder samples and its aliquant was analyzed along with Y000593 powders. The Nakhla powder sample is mentioned as Nakhla,55p, hereafter. (Note that Nakhla,55 designates the lump sample.) Sample descriptions are summarized in Table 1.

2.2 *PGA procedure*

The samples were sealed into thin FEP film bags and were irradiated for two hours

Table 1. Sample descriptions of nakhlites analyzed in this study.

Sample	type	rough size [mm]	weight [g]
Y000593,66	lump	11 x 10 x 6	1.2032
Y000749,46	lump	24 x 10 x 10	3.6126
Nakhla,55	lump	11 x 12 x 3	0.8809
Y000593,40	powder	(2.45)*	0.1103
Y000593,41	powder	(3.59)*	0.1107
Y000593,42	powder	(2.00)*	0.1032
Y000593,43	powder	(2.59)*	0.1041
Y000593,44	powder	(2.02)*	0.1043
Y000593,45	powder	(2.58)*	0.1098
Nakhla,55(p)	powder	(0.881)*	0.1217

*original mass [in g] before grinding to powder.

by cold neutrons (flux: 1.4×10^8 n $cm^{-2}s^{-1}$) guided out of a research reactor JRR-3M at JAERI. The neutron beam was collimated to the size of 20 mm×20 mm at the entrance of a sample box, which is filled with helium gas. Prompt gamma-rays were detected by a Ge detector coupled with a 16k channel pulse-height analyzer. The Ge detector is surrounded by bismuth germanium oxide (BGO) detectors so that signals due to Compton gamma-rays induced by high energy prompt gamma-rays are effectively suppressed by measuring coincident signals from Ge and BGO detectors.

As mentioned above, Y000593,66, Y000749,46 and Nakhla,55 were analyzed as lump samples. Among them, only Y000749,46 is larger than the neutron beam in size. Therefore, an internal mono-standard method (Sueki *et al.*, 1996) was to be applied to this sample for calculating elemental compositions. Two other meteorites of lumps were analyzed both by internal mono-standard method and by comparison method. Powdered samples were analyzed only by comparison method. By internal mono-standard method, only relative abundances to Si contents are obtained whereas comparison method yields absolute values of elemental contents. For comparison method, JB-1 (a geological standard rock sample issued by the Geological Survey of Japan) was used as a reference standard. Besides this, chemical reagent samples were prepared for the determination of H, B, Mg, Cl, S, Cr, Ni and Co. In calculating absolute contents of elements, an error due to the fluctuation of neutron beam (about 2.5% in one day; Yonezawa *et al.*, 1993) was not considered. Such an error is not involved in principle in internal mono-standard method.

3. Results and discussion

3.1. Chemical characteristics of Y000593 and Y000749

3.1.1. A possibility of pairing of Y000593 and Y000749

PGA results for lump specimens of three meteorites (Y000593,66, Y000749,46 and Nakhlite,55) are summarized in Table 2. Because the size of Y000749,46 is larger than

Table 2. PGA results for lump samples.[a]

Element[b]	Y000749,46	Y000593,66		Nakhla,55	Nakhla[d]
	(I)[c]	(I)	(II)[c]	(II)	
H, %	0.00242±0.00009	0.00266±0.00011	0.0541±0.0014	0.0252±0.0010	
B, ppm	(1.16±0.11)x10^{-5}	(1.53±0.16)x10^{-5}	3.47±0.06	3.02±0.07	*4.6*
Na, %	0.0392±0.0012	0.0203±0.0013	0.432±0.03	0.447±0.025	*0.34±0.05*
Mg, %	0.281±0.010	0.304±0.014	6.26±0.26	6.93±0.29	*7.3±0.2*
Al, %	0.0516±0.0015	0.0448±0.0017	0.999±0.030	0.974±0.033	*0.89±0.11*
Si, %	1	1	22.2±0.4	23.5±0.4	*22.7±0.8*
Cl, ppm	(4.05±0.26)x10^{-4}	(2.77±0.33)x10^{-4}	52.9±6.1	872±13	*80*
K, %	0.00719±0.00031	0.00587±0.00038	0.119±0.007	0.117±0.007	*0.107±0.019*
Ca, %	0.441±0.015	0.446±0.015	10.2±0.3	10.8±0.5	*10.5±0.5*
Ti, %	0.0112±0.0002	0.0101±0.0002	0.218±0.004	0.208±0.004	*0.202±0.025*
Cr, %	0.00763±0.00027	0.00826±0.00038	0.179±0.006	0.208±0.007	*0.177±0.028*
Mn, %	0.0178±0.0005	0.0188±0.0006	0.398±0.027	0.388±0.03	*0.382±0.31*
Fe, %	0.776±0.014	0.827±0.017	15.3±0.5	14.5±0.4	*16.0±1.2*
Co, ppm	(4.3±0.42)x10^{-5}	(4.7±0.6)x10^{-4}	91±11	79±12	*48±5*
Ni, ppm	(8.2±1.6)x10^{-4}	(8.7±2.3)x10^{-4}	179±48	191±55	*90*
Sm, ppm	(3.03±0.30)x10^{-6}	(6.34±0.33)x10^{-6}	1.46±0.09	1.01±0.07	*0.77±0.08*
Gd, ppm	(6.65±0.38)x10^{-6}	(6.19±0.47)x10^{-6}	1.17±0.09	1.08±0.07	*0.86±0.08*

a. Associated errors accompained with content values are originated from counting statistics.

b. Units in parentheses are applied to figures in columns 4 through 6.

c. I: Internal mono-standard method (relative contents); II: Comparison methods (absolute contents).

d. Compiled values (Lodders, 1998). Associated errors are standard deviations of several reported values.

the size of neutron beam used for PGA, only content ratios relative to Si content are given for this specimen. For comparison, Si-normalized contents for Y000593,66 also are listed in Table 2. These values were determined by internal mono-standard method. For Y000593,66 and Nakhla,55, absolute contents also can be calculated by using comparison method because whole specimens of these samples were irradiated with neutrons. These values are given in Table 2 along with compiled values for Nakhla (Lodders, 1998).

By comparing Si-normalized relative contents for Y000593,66 and Y000749,46, it is easily noticed that two sets of content values are reasonably consistent with each other for most elements. Exceptional are B, Na, Cl and Sm, whose values differ by larger than 30% between the two specimens. For such deviations, reasonable explanations can be given and some of them will be discussed later in detail. With these four elements being excluded, agreement becomes better. Among the remaining elements, Al and K seem to be relatively poor in consistency of contents between Y000593,66 and Y000749,46. Both elements are relatively depleted in Y000593,66 compared with those in Y000749,46. Such a depletion may be explained in terms of heterogeneous distribution of mesostasis. Except for these six elements, elemental contents are consistent between Y000593,66 and Y000749,46 within 10%, which corresponds to the reproducibility of analytical results by PGA (Oura *et al.*, 2002). It may be emphasized that most major and minor elements could be determined by PGA and that these elements show reasonable consistency in their abundances in Y000593,66 and Y000749,46. These observations support the suggestion from the petrographical observation and the field recognition that Y000593 and Y000749 are paired meteorites (Imae *et al.*, 2002).

3.1.2. Similarity in elemental composition between Y000593/Y000749 and Nakhla, and among nakhlites

Absolute contents of 17 elements calculated by comparison method (Table 2) imply a remarkable similarity between Y000593,66 and Nakhla,55 for most elements including major and minor elements. There seem to be large discrepancies in H and Cl contents between the two meteorites; H is enriched in Y000593,66 by a factor of two whereas Cl content in Nakhla,55 is 16 times larger. Samarium follows these two elements, being more abundant in Y000593,66 by 45%. Except these anomalous elements, only B, Cr and Co show relatively large but less meaningful difference of about 15%. As Co values have large (nominal) uncertainties, such a difference of 15% must be within these errors. A higher abundance of B in Y000593 may have its explanation as discussed later. For Cr, however, there seems to be no excuse; its difference of contents between two meteorites is just marginal if nominal errors due to counting statistics accompanied by individual content values and 10% allowance for PGA data are considered. Therefore, it is concluded that the similarity in elemental abundances between Y000593,66 and Nakhla,55 is in the same range as that between Y000593,66 and Y000749,46. This observation thus confirms the conclusion that Y000593 belongs to nakhlites (Imae *et al.*, 2002).

Our Nakhla values may be compared with its literature values (Lodders, 1998), which are cited in Table 2. It may be pointed that reported values for Nakhla have fairly large scatters for several elements; Cl, La, Sm and Sb show abundance ranges of

80–176 ppm, 1.14–5.37 ppm, 0.5–1.11 ppm and 4.6–250 ppm, respectively. These scatterings are apparently much larger than those observed in chondritic meteorites, as expected. In comparison of our data and literature values for Nakhla, a considerably large difference was observed for Cl, just in the same as for the comparison between Y000593,66 and Nakhla,55; our Cl value is 11 times higher than the compiled value. Both Co and Ni show the next largest difference; both elements seem to be more enriched in our specimen by a factor of ~2. As PGA data for these elements have relatively large uncertainties, such differences may not be considered seriously. Except for these three elements, our data are in reasonable agreement with literature values, confirming that PGA data are accurate and reliable enough for cosmochemical discussion.

Comparing our PGA data of Y000593,66 and Nakhla,55 with other nakhlites (Lafayette and Governador Valadares), elemental contents are similar within ±20% except for Cl, Mn, Na and K. An anomalously high abundance of Cl in our Nakhla,55 was already pointed out and is again confirmed in this comparison. Manganese, Na and K, which are cosmochemically grouped into relatively volatile elements, were observed to be slightly enriched in Governador Valadares compared with those in other nakhlites including Y000593. Interestingly, the degree of enrichment of these three elements increases with increasing their volatilities. As for major elements, there appears to be no distinguishable difference in their abundances among four nakhlites (Y000593, Nakhla, Lafayette and Governador Valadares).

3.2. Characterization of nakhlites and other Martian meteorites based on PGA data

PGA can be applied for the initial characterization of unidentified meteorite samples (Ebihara and Oura, 2001, 2003). This was effectively demonstrated for the Kobe meteorite (Oura *et al.*, 2002), which was consequently classified into CK meteorites based on PGA data only. Following the S/Mn *vs.* Al/Mn diagram applicable to carbonaceous chondrites, we have managed to draw a diagram based on PGA data, which is practical and equally effective for classifying Martian meteorites and even achondrites. Figure 1 is our solution for such demands. Apparently, three groups of Martian meteorites are plotted on their individual positions on this diagram. Nakhlite are located in a region characterized with high Ca/Si and low Mg/Si ratios, in which both Y000593 and Y000749 are included. Shergottites are spread on a line tying a point with high Ca/Si and low Mg/Si ratios and a point with low Ca/Mg and high Mg/Si ratios. Chassigny has an even lower Ca/Si ratio than those for shergottites but seems to be on the line represented by shergottites. ALH 84001, however, is clearly off the shergottite line, being a stray.

Figure 2a shows a Ca/Si *vs.* Mg/Si relationship for major groups of achondrites; they form an array and individual groups have their own segments. Howardites, eucrites and diogenites (HED) meteorites can be mostly separable on this diagram. Primitive achondrites tend to locate at the low end. Figure 2b is an enlargement of the rectangle located at bottom-left in Fig. 2a. Although the array of HED meteorites and the shergottite line seem to have the same end point member (about Mg/Si = 0.2 and Ca/Si = 0.25) on Fig. 2b, most Martian meteorites stay at their own locations, implying that Martian meteorites can be recognized as a group on the Ca/Si *vs.* Mg/Si diagram.

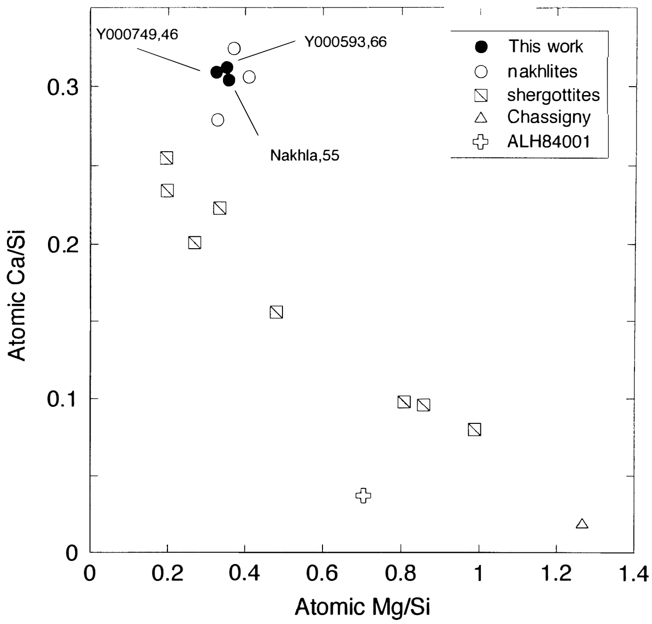

Fig. 1. Mg/Si–Ca/Si atomic ratios diagram for Martian meteorites. Closed circles and open symbols show our results and compiled data by Lodders (1998), respectively.

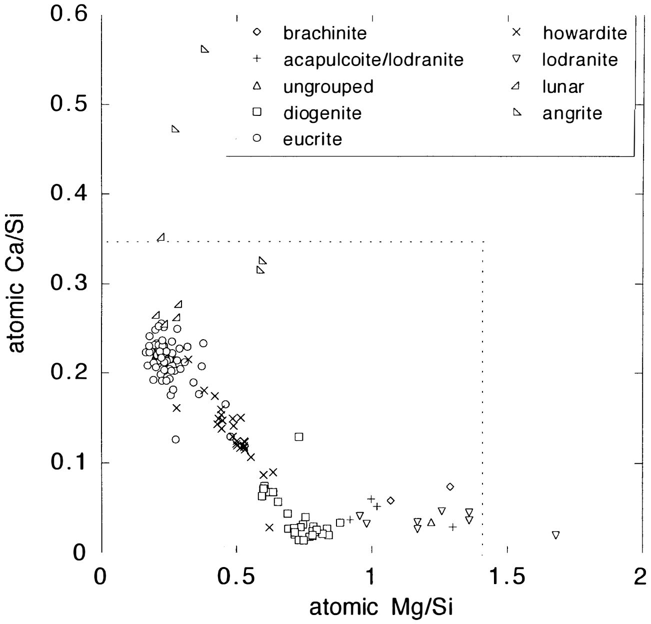

Fig. 2a. Mg/Si–Ca/Si atomic ratios diagram for achondrites. Dotted lines express the same region as Fig. 1.

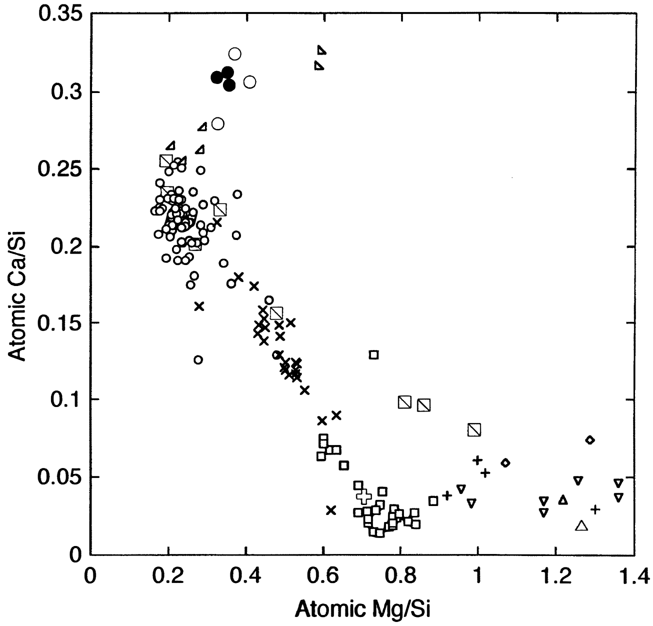

Fig. 2b. Expanded figure of the area shown by dotted line in Fig. 2a. Symbols are same as Fig. 1 and Fig. 2a. Larger symbols show Martian meteorites and smaller ones achondrites.

As already discussed, each subgroup of Martian meteorites can also be identified on the same diagram. Thus PGA can serve as a very effective tool for identifying not only chondritic meteorites but also achondritic meteorites. It may be pointed that ALH 84001 is located in the area designated for diogenites on this diagram. Actually, it was once mislabeled as a diogenite before being reclassified as a Martian meteorite. This fact, in turn, means that the diagram of Fig. 2 cannot serve for critical judgement.

3.3. Compositional heterogeneity of Y000593

As Y000593 is the largest nakhlite recovered so far, we intended to evaluate the compositional homogeneity/heterogeneity by analyzing replicate specimens sampled from 6 different positions. These samples were analyzed by PGA coupled with comparison method and their calculation data are given in Table 3. Figure 3 shows relative abundances of major and trace elements determined. In this figure, data are normalized to their mean values for individual elements. In Table 3, standard deviations (1σ) of six analytical data are given. Generally, standard deviations for most major and minor elements are about 10% or smaller. Thus, these elements (Na, Mg, Al, Si, K, Ca, Ti, Cr, Mn and Fe) are concluded to be homogeneous in elemental composition in a scale of 2–3 g in Y000593. Relatively large deviations are observed for Na, Mg, Al, K and Cr. These elements have generally poor counting statistics of more than 10% (1σ), among which K shows an exceptionally large value of 18%. In comparison of Y000593 and Y000749, we observed that Al and K contents are not consistent, possible due to the heterogeneous distribution of mesostasis. Similarly large

Table 3. PGA results for powder samples.[a]

	Y000593								Nakhla,55p[e]
	,40[b]	,41	,42	,43	,44	,45	mean[c]	counting[d]	
H, %	0.0642(40)	0.0592(38)	0.0718(43)	0.0685(41)	0.0739(42)	0.118(5)	0.0759(8%)	4%	0.0442(35)
B, ppm	4.50(19)	4.58(19)	3.10(13)	2.91(18)	3.74(20)	3.01(18)	3.64(21%)	5%	3.31(18)
Na, %	0.57(7)	0.50(6)	0.57(29)	0.68(7)	0.41(6)	0.46(7)	0.53(19%)	12%	0.61(7)
Mg, %	6.3(7)	5.3(6)	5.5(6)	7.0(7)	6.1(6)	6.1(6)	6.1(11%)	10%	8.0(7)
Al, %	1.00(11)	1.10(11)	1.05(12)	0.96(11)	1.32(11)	0.934(109)	1.06(13%)	10%	0.866(110)
Si, %	22.3(6)	22.3(6)	22.2(7)	22.2(6)	21.8(7)	22.6(7)	22.2(1%)	2%	22.5(6)
Cl, ppm	130(20)	130(20)	80(20)	82(20)	130(30)	140(20)	120(23%)	20%	1070(40)
K, %	0.11(2)	0.11(2)	0.15(2)	0.13(2)	0.13(2)	0.13(2)	0.13(13%)	18%	0.16(2)
Ca, %	10.2(3)	10.1(3)	10.3(3)	9.67(26)	10.4(3)	10.3(3)	10.2(3%)	2%	10.8(3)
Ti, %	0.236(3)	0.236(9)	0.240(9)	0.224(9)	0.247(9)	0.246(9)	0.238(4%)	4%	0.210(8)
Cr, %	0.183(15)	0.191(21)	0.215(23)	0.190(21)	0.240(23)	0.242(22)	0.210(11%)	10%	0.229(21)
Mn, %	0.392(32)	0.415(34)	0.365(31)	0.405(33)	0.421(35)	0.420(34)	0.403(6%)	4%	0.397(33)
Fe, %	17.5(7)	17.8(7)	17.4(7)	17.3(7)	17.4(7)	17.2(7)	17.4(1%)	2%	16.0(7)
Co, ppm	120(30)	81(28)	76(29)	200(40)	69(46)	140(40)	110(48%)	36%	180(40)
Sm, ppm	1.89(13)	1.57(11)	1.88(14)	1.41(10)	1.47(11)	1.37(10)	1.60(14%)	6%	1.11(9)
Gd, ppm	1.2(2)	1.2(2)	1.3(2)	0.94(20)	1.2(2)	0.94(19)	1.1(12%)	19%	0.87(19)

a. Figures in parentheses are statistical errors (1σ), corresponding to the last digit(s).
b. Subnumbers.
c. Mean values of six Y000593 specimens. Figures in parentheses are relative standard deviations (1σ).
d. Mean statistical errors of prompt gamma-ray counting for 6 specimens.
e. Powdered Nakhla,55 (See Table 1 and text).

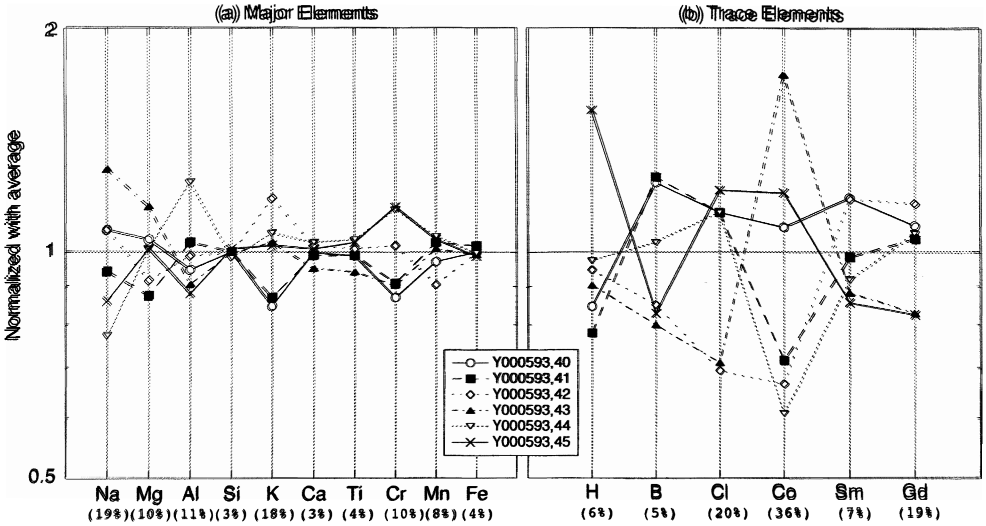

Fig. 3. Comparison of elemental contents in 6 specimens of Y000593. Normalized values with each averages are plotted. (a) major elements and (b) trace elements. The figures in parenthesis shown under element names are mean of relative errors of 6 each determinations.

standard deviations of Al and K among six aliquant samples can also be explained in terms of its heterogeneous distribution. A relatively large deviation of Na may be explained similarly, although the deviation does not seem to be well correlated among Na, Al and K. Trace element abundances show relatively large deviations, as expected. In principle, poor statistics in gamma ray counting yielded these large values. Exceptions are H and B, whose counting statistics are smaller than 10% (1σ). Apparently, these elements are distributed heterogeneously. Thus, it can be concluded that most major and minor elements are distributed within $\pm 10\%$ (1σ), which is equivalent to the reproducibility of data in PGA, and, hence, these elements are homogeneously present in Y000593 (or nakhlites in general) within $\pm 10\%$ (1σ).

3.4 Some insights of elemental abundances in the Y000593 nakhlite

3.4.1. Hydrogen

According to the recent observation by Mars Odyssey, the presence of ice on the Mars subsurface is highly expected (Boynton *et al.*, 2002). In fact, some minerals containing water were found in Martian meteorites (Ashworth and Hutchison, 1975). The presence of water on the Mars surface was also suggested from the observation of the surface morphology, *e.g.*, a trace of water stream. In relation to these observations and suggestions, water contents (or H abundances) have been concerned and consequently determined for Martian meteorites. Hydrogen contents in Martian meteorites have been determined mainly by using pyrolysis and combustion methods to expel the hydrogen with heating samples. For these methods, relatively large amount of samples (normally more than 500 mg) are required. Because H is one of the most sensitive elements in PGA, it could be determined along with major and trace elements only for

100 mg of samples nondestructively in this study. Our PGA results for H are summarized in Table 4, in which some our unpublished data for ALH77005, EETA 79001 and ALH84001 are given along with literature values for Martian meteorite. It is noticed in Table 4 that our values are all systematically higher than literature values for any Martian meteorite when comparisons are possible.

Hydrogen contents in Y000593 from this study vary by a factor of two from 0.0541 % (Y000593,66; lump) to 0.118% (Y000593,45; powder). A similarly lower abundance is observed in another lump sample (Y000749,46). This systematic difference suggests that relatively high contents of H for powder samples are contributed by moisture adsorbed on the surface of powder samples. A similar systematic difference between lump and powder samples was also found for Nakhla; H content of its lump sample (Nakhla,55) is 45% lower than that of the powdered Nakhla (Nakhla,55p). As the lump sample was sealed into a FEP film bag immediately after opening the sealed can container, the contribution of moisture must be less significant. Nevertheless, our value for the lump Nakhla sample is two times higher than the literature values (Leshin *et al.*, 1992; Karlsson *et al.*, 1992). In those studies, samples were pretreated to expel the adsorbed H_2O in different ways and H contents were determined after H was converted from water (H_2O) released upon heating of samples. We did not treat our samples in such a way, which must account for systematically higher values of H in this study than the literature values. In PGA, JB-1 and the Smithsonian Allende reference meteorite are routinely analyzed and their H contents obtained in this study were 0.203 $\pm$0.006% and 0.026$\pm$0.002% (errors are counting statistics; 1σ), respectively. This H value of JB-1 is consistent with the certified value of H_2O (1.97%), which corresponds to 0.22% for H. For JB-1, H_2O (−) (weight loss by heating at 110°C) is 48% of the total H_2O. Therefore, we suspect that the difference in H contents between our PGA data and corresponding literature values are too large to be explained only by the difference in the pretreatment of samples. Further experiments are now in progress for determining H contents under strict control.

3.4.2. Boron

Boron is well acknowledged for its susceptibility to the terrestrial contamination (Curtis *et al.*, 1980). Considering this, our values for nakhlites may be admitted to be rather constant. Boron contents of powder samples of Y000593 vary from 2.91 ppm to 4.58 ppm, with a mean value of 3.64 ppm. Two additional values for lump samples fall in this range, yielding a weighted mean of 3.46 ppm for all Y000593 and Y000749 samples (Si content of Y000749 was assumed to be the same as that of Y000593,66; 22.2 %). Our two Nakhla data (3.02 and 3.31 ppm) are close to each other, and also close to these mean values. As the Nakhla sample analyzed in this study has not suffered from contamination, the similarity of B contents between Nakhla and Y000593/ Y000749 suggests that these two Yamato nakhlites are scarcely contaminated with B. Thus, we propose a weighted mean of our all B data for nakhlites, 3.33 ppm as a B content of nakhlites. A fairly large variation of B contents observed in Y000593 powder samples (or among nakhlites) may reflect its heterogeneous distribution rather than contamination.

3.4.3. Chlorine

There can be seen a noticeable variation in Cl contents in Nakhla, as already

Table 4. Comparison of H contents in Martian meteorites (in %).[a]

Nakhlite		Shergottite		Chassigny		Other	
Nakhla,55	0.0252(10)	Shergotty (S1)	0.00464[b]	Chassigny (C1)	0.0141[b]	ALH84001	0.024(3)[f]
Nakhla,55p	0.0442(35)	Shergotty	0.0072[c]	Chassigny (C2)	0.0106[b]		
Nakhla (N1)	0.0142[b]	Shergotty	0.00133[d]	Chassigny (C3)	0.00387[b]		
Nakhla (N2)	0.0138[b]	Zagami (Z1)	0.00423[b]	Chassigny	0.0114[c]		
Nakhla(N3)	0.0126[b]	Zagami-1	0.0047[c]				
Nakhla (N4)	0.0121[b]	Zagami-2	0.0048[c]				
Nakhla (N5)	0.0126[b]	EETA79001	0.023(3)[f]				
Nakhla	0.0128[c]	EETA79001(EA1)	0.00675[b]				
Lafayette (L1)	0.0430[b]	EETA79001A	0.0072[c]				
Lafayette (L2)	0.0417[b]	ALH77005	0.0091(21)[f]				
Lafayette	0.0433[c]						
Lafayette	0.00583[d]						
Governador Valadares (GV1)	0.0123[b]						
Y000593,40	0.0642(40)						
Y000593,41	0.0592(38)						
Y000593,42	0.0718(43)						
Y000593,43	0.0685(41)						
Y000593,44	0.0739(42)						
Y000593,45	0.118(5)						
Y000593,66	0.0541(14)						
Y000749,46	0.0537(20)[e]						

a. Underlined values are PGA data from our lab. Values for ALH 77005, EET 79001 and ALH 84001 are unpublished data and given for information only. The figures in parentheses are statistical errors (1σ), corresponding to the last digit(s).

b. Leshin *et al.* (1996).

c. Karlsson *et al.* (1992). Hydrogen contents are calculated from bulk H_2O contents.

d. Kerridge (1988).

e. Assuming that the Si content is the same as that for Y000593,66.

f. Unpublished values.

pointed. Chlorine content of Y000593,66 is 30% lower than that of Y000749,46 (both are lump samples). Among six powder samples of Y000593, Cl content vary from 80 ppm to 141 ppm, with a mean value of 120 ppm. It is well admitted that some Antarctic meteorites have overabundances of halogens, especially chlorine and iodine (*e.g.*, Dreibus and Wänke, 1983; Shinonaga *et al.*, 1994). Such an overabundance is significant in the surface layer and the degree of overabundance decreases toward the center of meteorites (e.g., Ebihara *et al.*, 1990; Langenauer and Krähenbühl, 1993). As we used the interior portions of Y000593 and Y000749 for PGA, the contribution of terrestrial contamination seems to be negligible for both samples. Another issue for the abundance of halogens among meteorites is their heterogeneous distribution (*e.g.*, Zolensky *et al.*, 1999; Kato *et al.*, 2000). The heterogeneous distribution of chlorine can explain a large difference in its contents between Nakhla,55 and other nakhlites. A similarly large difference between our Nakhla values and its literature values may also be explained in such a line. As our Nakhla sample was taken from the interior of the meteorite and a great care was paid in analyzing it, an anomalously high abundance of Cl in the Nakhla,55 sample must be indigenous. Considering sampling processes (sample weights and sampling positions) for Y000593 powders, we may propose a mean Cl content of nakhlites as 120 ppm, a mean value of six determinations, which gets slightly decreased to 80 ppm (as a weighted mean) if a value for a lump sample is included.

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