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The Yamato nakhlite consortium

Keiji Misawa[1,2], Hideyasu Kojima[1], Naoya Imae[1] and Noboru Nakamura[3]

[1]*Antarctic Meteorite Research Center, National Institute of Polar Research,*
[2]*Department of Polar Science, School of Mathematics & Physics, Graduate University of Advanced Studies, Kaga 1-chome, Itabashi-ku, Tokyo 173–8515*
[3]*Department of Earth & Planetary Sciences, Kobe University, 1–1, Rokkodai-cho, Nada-ku, Kobe 657–8501*

Abstract: Among 3550 meteorite samples found near the Yamato Mountains area during the field season of 2000–2001, three meteorites, Yamato (Y) 000593, Y000749, and Y000802 of total weight of about 15 kg, are identified as new paired nakhlites. In ordered to improve our knowledge of the nakhlite parent body, possibly Mars, a coordinated consortium study of the Yamato nakhlites was organized. We here present an outline of the Yamato nakhlite consortium and implications for Martian geological history on the basis of ongoing studies.

key words: nakhlites, Martian meteorites, Y000593, Y000749, Y000802

1. Introduction

The wintering party of the 41st Japanese Antarctic Research Expedition conducted a meteorite search during the Antarctic summer field season of 2000–2001 in the bare ice field near the Yamato Mountains area (Imae *et al.*, 2002a). Among 3550 meteorites found, Yamato 000593 (hereafter Y000593), Y000749, and Y000802 were identified as nakhlites (Kojima and Imae, 2001; Imae *et al.*, 2002b; Kojima *et al.*, 2002). Nakhlites are rare clinopyroxene-rich cumulate rocks of probable Martian origin (*e.g.*, McSween, 1994). A total of eight meteorites, Nakhla, Lafayette, Governador Valadares, North West Africa (hereafter NWA) 817 (Sautter *et al.*, 2002), Yamato (Y000593, Y000749, and Y000802), and NWA998 (Irving *et al.*, 2002; Russell, 2003), have thus far been identified as nakhlites.

After the announcement of the new Antarctic nakhlites (Kojima and Imae, 2001), more than twenty sample requests for investigation were received. At a meeting held on 19 March 2002 the Committee on Antarctic Meteorite Research recognized the need for a coordinated consortium study of the Yamato nakhlites and approved H. Kojima (NIPR) and N. Nakamura (Kobe Univ.) to lead this consortium.

The goals of this consortium: first, to identify similarities and differences between Yamato and non-Antarctic nakhlites; second, to constrain chemical and isotopic signatures of the nakhlite source(s); third, to evaluate mechanisms of low-temperature aqueous alteration on Martian surface, and last, to identify the nature of nakhlite-Chassigny source crater. Results from some of the consortium studies were presented at the 27th NIPR Symposium on Antarctic Meteorites and are reported in the present volume.

2. Yamato nakhlites overview

On 29th November 2000, Y000593 was collected in the bare ice field ~10 km north from the northern end of the JARE IV Nunataks (Fig. 1). Four days later both Y000749 and Y000802 were found. These specimens were collected in a small area, within 1 km^2, suggesting they are paired. The largest, Y000593, is 13.7 kg in weight and is the heaviest achondritic sample so far recovered in Antarctica (Figs. 2 and 3a). The second specimen, Y000749 (Fig. 3b), is 1.28 kg in weight and shows similar macroscopic texture as Y000593. A small 22-g meteorite, Y000802 (Fig. 3c), was later identified as the third Yamato nakhlite (Kojima *et al.*, 2002).

All three Yamato nakhlites are half covered with shiny black-colored fusion crust with ablation features. However, these stones have experienced some surficial weathering and in some places are deeply eroded. This weathering features may be due to the heavy katabatic wind blowing predominantly from east on the sampling site, because the physically eroded surface of Y000593 turned to the east in the field. Pyroxene and olivine crystals could be easily identified with the naked eye. All the specimens are quite fragile. We cannot determine the spatial relationships of these three meteorites to one another, suggesting that they may represent individual stones of a meteorite shower.

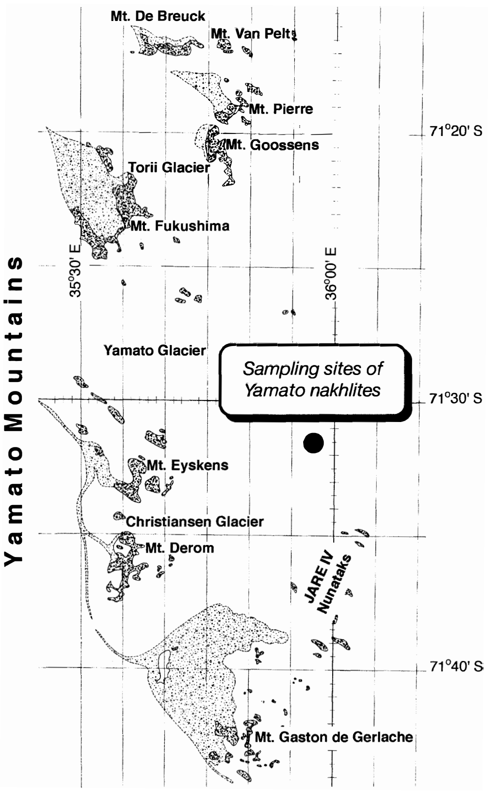

Fig. 1. The sampling sites of the Yamato nakhlites. Yamato 000593 was collected at 71°30.147′ S, 35°57.745′ E and a height of ~1890 m above sea level. The Yamato nakhlites were collected in a small area, within 1 km².

Fig. 2. *Occurrence of Yamato 000593 in the bare ice field of the Yamato Mountains area. The specimen is partly covered with black fusion crust, showing green colored interior.*

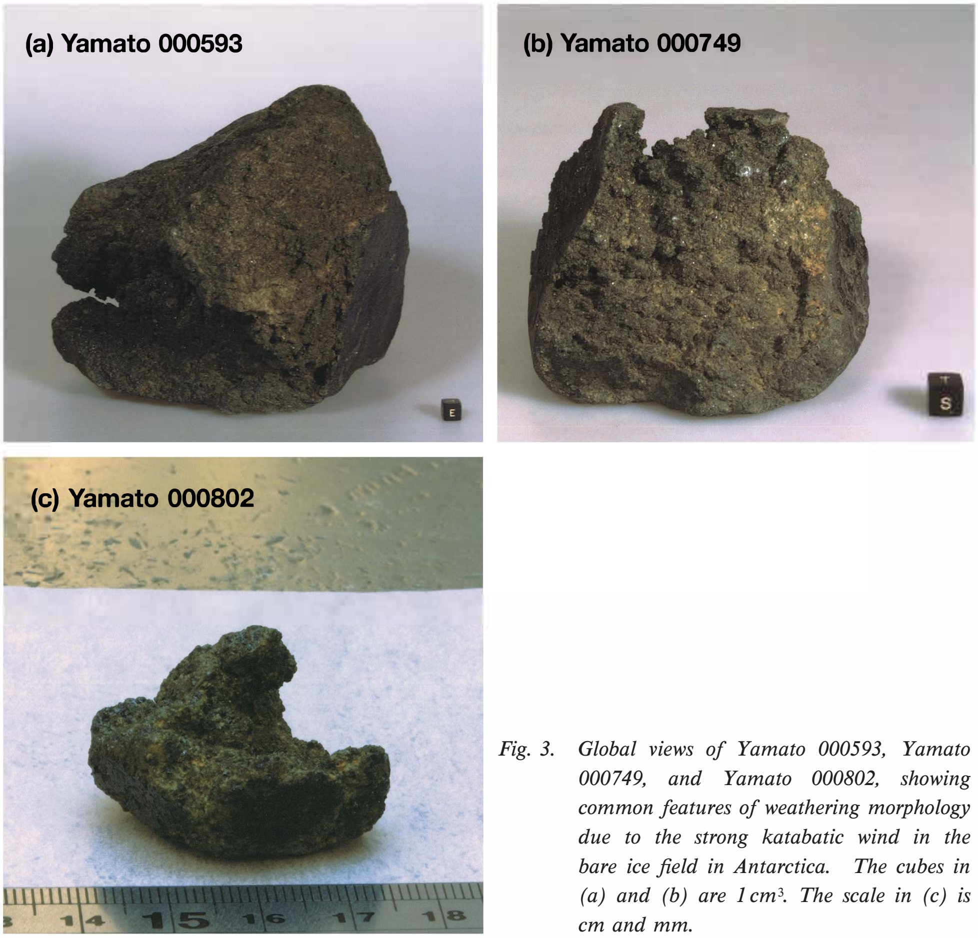

Fig. 3. *Global views of Yamato 000593, Yamato 000749, and Yamato 000802, showing common features of weathering morphology due to the strong katabatic wind in the bare ice field in Antarctica. The cubes in (a) and (b) are 1 cm³. The scale in (c) is cm and mm.*

3. Curatorial processing of Yamato nakhlites

Two 2 g-sized fragments, Y000593,64 (2.180 g) and Y000749,47 (2.014 g), were used for wet chemical analysis at NIPR. After the identification of these nakhlites, two 90 mg-sized samples (Y000593,70 and Y000749,70) were allocated to R. Clayton (Univ. Chicago) for measurements of oxygen isotopes. Even before the consortium commenced, Y000749,40 (205 mg) was allocated to R. Okazaki (Univ. Tokyo) for rare gas study that confirmed Y000749 is a nakhlite. In addition to this sample, K. Nagao (Univ. Tokyo) received a 506 mg sample (Y000593,65) for rare gas geochemistry. A mass of 227 mg (Y000802,60) was allocated to R. Okazaki (Univ. Tokyo) for rare gas study.

Initial sample processing for the consortium took place in the Antarctic Meteorite Research Center at NIPR, using stainless steel tools. Samples of Y000593 for polished thin sections (PTSs) and for chemical analyses were taken from a limited interior portion of the main mass (Fig. 4). Most samples were sent to investigators in April 2002. After initial processing, a homogenized powder sample weighing about 15 g was prepared from six randomly selected chips from a large area. These chips of Y000593,40-45 ranged in weight from 2 to 3 g. Using 200 mg-sized aliquots (Y000593,40,1, 41,1, 42,1, 43,1, 44,1, 45,1), M. Ebihara (Tokyo Metropolitan Univ.) investigated heterogeneity of the powdered sample. For bulk analysis this sample is available upon request.

A mass of 4.9 g (Y000593,54) was allocated to M. Grady's consortium of UK scientists. The samples will be used for mineralogy and petrology (M. Grady, NHM, London), for noble gas chemistry and ^{129}I-^{129}Xe, ^{40}K-^{40}Ar, and ^{39}Ar-^{40}Ar dating (G. Turner, Univ. Manchester), and for light element geochemistry and oxygen isotope compositions (C. Pillinger, Open Univ.). Two large fragments, Y000593,66 (1.211 g) and Y000749,46 (3.663 g), were allocated to M. Ebihara for nondestructive neutron induced prompt gamma-ray analysis (PGA). An offcut (Y000593,00-01) was allocated to A. El Goresy (MPI, Mainz) to estimate the temperature-fO_2 conditions using Fe-Ti partitioning between titanomagnetite and ilmenite. T. Mikouchi (Univ. Tokyo) received a 439-mg sample (Y000593,88) for transmitted electron microscopy (TEM) of augite and symplectite in olivine. D. Stöffler (Humboldt Univ.) received Y000593,75 (1.102 g) to study shock effects on the Yamato nakhlites. T. Hiroi (Brown Univ.) and M. Miyamoto (Univ. Tokyo) received 62-mg (Y000593,90) and 651-mg (Y000593,86) samples, respectively, for reflectance spectroscopy. N. Imae (NIPR) received Y000593,57 and ,58 (3.171 g and 0.796 g, respectively), and Y000749,49 (1.190 g) to investigate absorption spectra of OH using Fourier transform infrared (FTIR) spectroscopy. Fragments weighing a total of 4.256 g (Y000592,55) were allocated to N. Nakamura (Kobe Univ.) for the Rb-Sr, Sm-Nd, and U-Pb isotope systematics, and for the determination of chlorine isotopic compositions and lithophile trace element abundances by thermal ionization mass spectrometry (TIMS). G. Dreibus (MPI, Mainz) received a 1.371-g sample (Y000593,81) for the determination of Rb-Sr, Sm-Nd and U-Pb ages and for the determination of trace element abundances with instrumental neutron activation analysis (INAA). The NASA-JSC group led by L. Nyquist received fragments weighing a total of 2.265 g. Together with JSC personnel D. Bogard

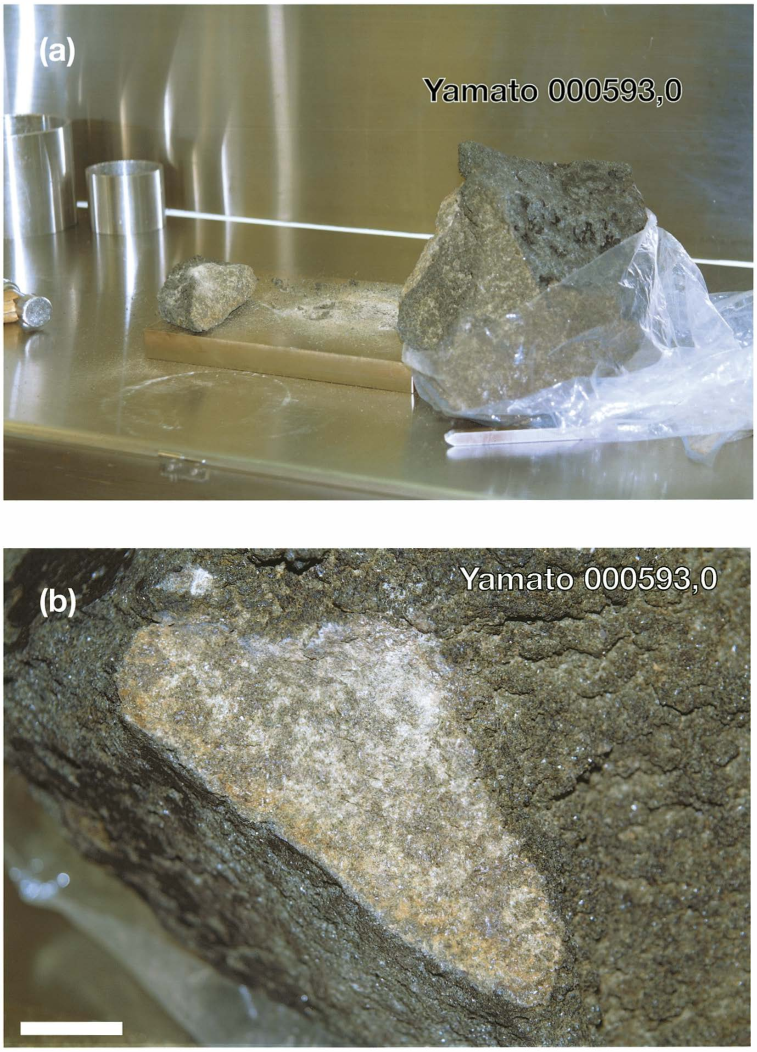

Fig. 4. Sample processing of Yamato 000593.
(a) Many allocated samples were taken from a limited interior portion of the main mass, Yamato 000593,0.
(b) Fresh broken surface of Yamato 000593,0. Scale bar is 2 cm.

and C.-Y. Shih (Lockheed-Martin), he will determine crystallization age by the Rb-Sr, Sm-Nd, and ^{39}Ar-^{40}Ar systems, mantle differentiated age by the ^{146}Sm-^{142}Nd system, and neutron capture effects by ^{149}Sm and ^{150}Sm isotopes. Two chips (Y000593,87 and Y000749,52) weighing 487 mg and 616 mg, respectively, were allocated to P. Warren (UCLA) for study of bulk compositions especially focused on siderophile element abundances using INAA and radiochemical neutron activation analysis (RNAA) as clues to Martian core-mantle differentiation. K. Marti (UCSD) received Y000593,85 (685 mg) and Y000749,51 (462 mg) for identification of fission, spallation, and indige-

Table 1. Distribution of samples for the Yamato nakhlite consortium, including PTS samples.

Yamato 000593 (13.713 kg) Subnumber	Weight (gram)	Investigator	Institution	Type of investigation
35	3.227	McKay, G.	NASA-JSC	Re-Os
40	2.447		NIPR	bulk chemistry (powdered)
41	3.591		NIPR	bulk chemistry (powdered)
42	2.000		NIPR	bulk chemistry (powdered)
43	2.591		NIPR	bulk chemistry (powdered)
44	2.109		NIPR	bulk chemistry (powdered)
45	2.577		NIPR	bulk chemistry (powdered)
54	4.922	Grady, M.	NHM, London	UK consortium
55	4.256	Nakamura, N.	Kobe Univ.	chronology & chemistry
56	2.256	Nyquist, L.	NASA-JSC	chronology
57	3.171	Imae, N.	NIPR	FTIR
58	0.796	Imae, N.	NIPR	FTIR
59	1.172	Nishiizumi, K.	Space Sci. Lab., UCB	CRE
60	1.060	Nishiizumi, K.	Space Sci. Lab., UCB	CRE
61	0.607		NIPR	PTSs
62	2.248		NIPR	PTSs
63	1.884		NIPR	PTSs
64	2.180		NIPR	PTSs
65	0.506	Nagao, K.	Univ. Tokyo	rare gas
66	1.212	Ebihara, M.	Tokyo Metropolitan Univ.	PGA
67	1.011		NIPR	PTSs
68	2.230		NIPR	PTSs
69	0.227	Hidaka, H.	Hiroshima Univ.	neutron exposure effects
70	0.093	Clayton, R.	Univ. Chicago	oxygen isotope
71	0.871	Funaki, M.	NIPR	rock magnetism
72	0.716	Funaki, M.	NIPR	rock magnetism
73	0.918	Okazaki, R.	Univ. Tokyo	rare gas
74	1.212	Nakamuta, Y.	Kyushu Univ.	alteration products
75	1.102	Stöffler, D.	Humboldt Univ.	shock effects
76	0.719	Noguchi, T.	Ibaraki Univ.	TEM
79	0.507	Mikouchi, T.	Univ. Tokyo	shock experiment
81	1.371	Dreibus, G	MPI, Mainz	chemistry & chronology
82	0.938	Shinoda, K.	Osaka City Univ.	FTIR
84	0.796	Murty, S.	Phys. Res. Lab., Ahmedabad	CRE, rare gas & nitrogen isotope
85	0.685	Marti, K.	UCSD	nitrogen, argon & xenon isotopes
86	0.651	Miyamoto, M.	Univ. Tokyo	reflectance spectroscopy
87	0.487	Warren, P.	UCLA	INAA & RNAA
88	0.493	Mikouchi, T.	Univ. Tokyo	TEM
90	0.062	Hiroi, T.	Brown Univ.	reflectance spectroscopy
91	0.086	Murty, S.	Phys. Res. Lab., Ahmedabad	CRE, rare gas & nitrogen isotope
92	0.156	Murty, S.	Phys. Res. Lab., Ahmedabad	CRE, rare gas & nitrogen isotope
93	0.127	Murty, S.	Phys. Res. Lab., Ahmedabad	CRE, rare gas & nitrogen isotope
94	0.258	Murty, S.	Phys. Res. Lab., Ahmedabad	CRE, rare gas & nitrogen isotope
95	0.222	Murty, S.	Phys. Res. Lab., Ahmedabad	CRE, rare gas & nitrogen isotope
102	0.338	Herzog, G.	Rutgers Univ.	CRE
103	0.355	Eugster, O	Univ. Bern	CRE
115	0.091	Halliday, A.	ETH	Hf-W
00-01	offcut	El Goresy, A.	MPI, Mainz	temperature & oxygen fugacity

PTSs; Y000593,61-1 & ,67-1: Imae, N. (NIPR), Y000593,62-1: Terada, K. (Hiroshima Univ.), Y000593,62-2: Goodrich, C. (Univ. Hawaii), Y000593,62-3 ,62-6 & ,68-1: Mikouchi, T. (Univ. Tokyo), Y000593,62-4: McCoy, T. (USNM), Y000593,63-1: Warren, P. (UCLA), Y000593,63-2: Ikeda, Y. (Ibaraki Univ.), Y000593,63-4 & ,63-6: Nakamura, N. (Kobe Univ.), Y000593,63-5: Wadhwa, M. (FMNH), Y000593,67-2: McKay, G. (NASA-JSC), Y000593,68-2: Shinoda, K. (Osaka City Univ.).

Table 1 (continued).

Yamato 000749 (1.283 kg)				
Subnumber	**Weight (gram)**	**Investigator**	**Institution**	**Type of investigation**
1	1.415		NIPR	PTSs
5	5.401		NIPR	PTSs
40	0.205	Okazaki, R.	Univ. Tokyo	rare gas
46	3.663	Ebihara, M.	Tokyo Metropolitan Univ.	PGA
47	2.014		NIPR	PTSs
48	1.048	Dreibus, G.	MPI, Mainz	chemistry & chronology
49	1.190	Imae, N.	NIPR	FTIR
50	0.996	Nishiizumi, K.	Space Sci. Lab., UCB	CRE
51	0.462	Marti, K.	UCSD	nitrogen, argon & xenon isotopes
52	0.616	Warren, P.	UCLA	INAA & RNAA
53	0.678	Okazaki, R.	Univ. Tokyo	rare gas
54	0.289	Herzog, G.	Rutgers Univ.	CRE
55	0.234	Hidaka, H.	Hiroshima Univ.	neutron exposure effects
56	0.466	Nakamuta, Y.	Kyushu Univ.	alteration products
57	0.891	Noguchi, T.	Ibaraki Univ.	alteration products
58	0.938	Shinoda, K.	Osaka City Univ.	FTIR
61	0.419	Eugster, O	Univ. Bern	CRE
70	0.090	Clayton, R.	Univ. Chicago	oxygen isotope
71	0.082	Halliday, A.	ETH	Hf-W

PTSs; Y000749,1-1: Imae, N. (NIPR), Y000749,1-3: Ikeda, Y. (Ibaraki Univ.), Y000749,1-6: Shinoda, K. (Osaka City Univ.), Y000749,5-1: Goodrich, C. (Univ. Hawaii), Y000749,5-2: Warren, P. (UCLA), Y000749,5-3: McCoy, T. (USNM), Y000749,5-4: Terada, K. (Hiroshima Univ.), Y000749,5-5: Wadhwa, M. (FMNH).

Yamato 000802 (22.306 g)				
Subnumber	**Weight (gram)**	**Investigator**	**Institution**	**Type of investigation**
20	1.593		NIPR	PTSs
60	0.227	Okazaki, R.	Univ. Tokyo	rare gas
61	0.215	Nishiizumi, K.	Space Sci. Lab., UCB	CRE

PTS; Y000802,20-1: Imae, N. (NIPR).

nous components of nitrogen, argon, and xenon in the source region of nakhlites. An interior chip, Y000593,84 (796 mg), and six samples of near surface material (Y000593,90-95) of a total weight of 911 mg were allocated to S. Murty (Phys. Res. Lab., Ahmedabad) to investigate cosmic-ray exposure ages (CRE), trapped noble gases, and nitrogen components. In order to study in detail the solar cosmic-ray effects and pre-atmospheric sizes of the Yamato nakhlites using ^{41}Ca, ^{36}Cl, ^{26}Al, ^{10}Be, and ^{53}Mn, K. Nishiizumi (Space Sci. Lab., UCB) was allocated a 1.172 g-sized interior sample (Y000593,59), a 1.060 g-sized exterior sample (Y000593,60), and a 996 mg-sized Y000749 chip (,50). Later he received a 215 mg-sized Y000802 chip (,61) adjacent to the sample allocated to R. Okazaki for rare gas studies. He split the allocated samples and sent aliquots of chips to A. Jull (Arizona Univ.) for ^{14}C measurement. H. Hidaka (Hiroshima Univ.) was allocated ~230 mg-sized samples (Y000593,69 and Y000749,55) to study neutron capture effects on samarium and gadolinium isotopes by TIMS. G. Herzog (Rutgers Univ.) received interior and fusion crust samples of Y000593,102 (338 mg) and Y000749,54 (289 mg) to study CRE by measuring nuclides ^{36}Cl, ^{26}Al, ^{10}Be, and ^{53}Mn using accelerating mass spectrometry (AMS). In order to study magnetic properties of nakhlites, M. Funaki (NIPR) received Y000593,71 (871 mg) and

Y000593,72 (716 mg).

Apart from those used for the initial classification, PTSs were produced for the Yamato nakhlite consortium, from four separate parent chips (Y000593,62, Y000593,63, Y000593,67, Y000593,68) and from one separate parent chip (Y000749,5) (*see* Table 1). We will produce PTSs using the samples allocated for PGA (Y000593,66 and Y000749,46). Five PTSs has been prepared from a parent chip of Y000802,20. Thus far, PTSs have been loaned to C. Goodrich (Univ. Hawaii), Y. Ikeda (Ibaraki Univ.), N. Imae (NIPR), T. McCoy (USNM), T. Mikouchi (Univ. Tokyo), N. Nakamura (Kobe Univ.), K. Terada (Hiroshima Univ.), M. Wadhwa (FMNH), and P. Warren (UCLA) for analysis of mineralogy and petrology. Four PTSs, Y000593,62-1, Y000749,5-4 (both loaned to K. Terada), Y000593,63-5, and Y000749,5-5 (both loaned to M. Wadhwa) will be used for ion microprobe analysis.

4. Results and discussion

4.1. *Mineralogy and petrology*

Imae *et al.* (2003) and Mikouchi *et al.* (2003) reported mineralogy and petrology of the Yamato nakhlites and concluded that they are most similar to Nakhla (Fig. 5). The Yamato nakhlites, unbrecciated cumulate rocks, are composed principally of augite and olivine. Modal abundances of augite, olivine, and mesostasis vary slightly between different sections and are roughly 70–85%, 10–20%, and 5–10%, respectively. The chemical composition of the augite core in the Yamato nakhlites is nearly identical to those of other nakhlites ($En_{40}Fs_{20}Wo_{40}$). Olivine in the Yamato nakhlites shows extensive chemical zoning (Fa_{60-80}). Olivine in the Yamato nakhlites contains magnetite-augite symplectic exolutions. Nearly identical symplectites have been found in Nakhla, Governador Valarades, and Chassigny (Yamada *et al.,* 1997; Greshake *et al.,* 2000; Mikouchi *et al.,* 2000) but have not been found in Lafayette. These inclusions may constrain the cooling rate of olivine under the relatively higher oxygen fugacity. Mesostasis predominantly consists of plagioclase with minor K-feldspar, augite, pigeonite, olivine, titanomagnetite, apatite, and silica. Preterrestrial aqueous alteration products (Bunch and Reid, 1975; Gooding *et al.,* 1991; Treiman *et al.,* 1993; Gillet *et al.,* 2002) are found in the Yamato nakhlites. They are reddish in color and may be composed of montmorillonite, goethite, saponite, and ferrihydrite (Treiman and Goodrich, 2002; Imae *et al.,* 2003).

The reflectance spectrum of Y000593 is similar to that of Nakhla, and is also similar to Lafayette except for differences in slope from 0.6–0.8 μm in wavelength (Ueda *et al.,* 2003)

4.2. *Bulk chemical composition*

The bulk compositions of Y000593 and Y000749 (see Table 1 of Imae *et al.,* 2003) are comparable to those of non-Antarctic nakhlites: enriched in iron, magnesium, and calcium. Using bulk powdered samples of Y000593, Oura *et al.* (2003) performed PGA, and examined whether or not chemical heterogeneities exist in a 2 g-sized sample of the Yamato nakhlites. The Ti/Ca ratios, which are one of the key elemental ratios for nakhlites, of six powdered samples from Y000593 display nearly constant values of

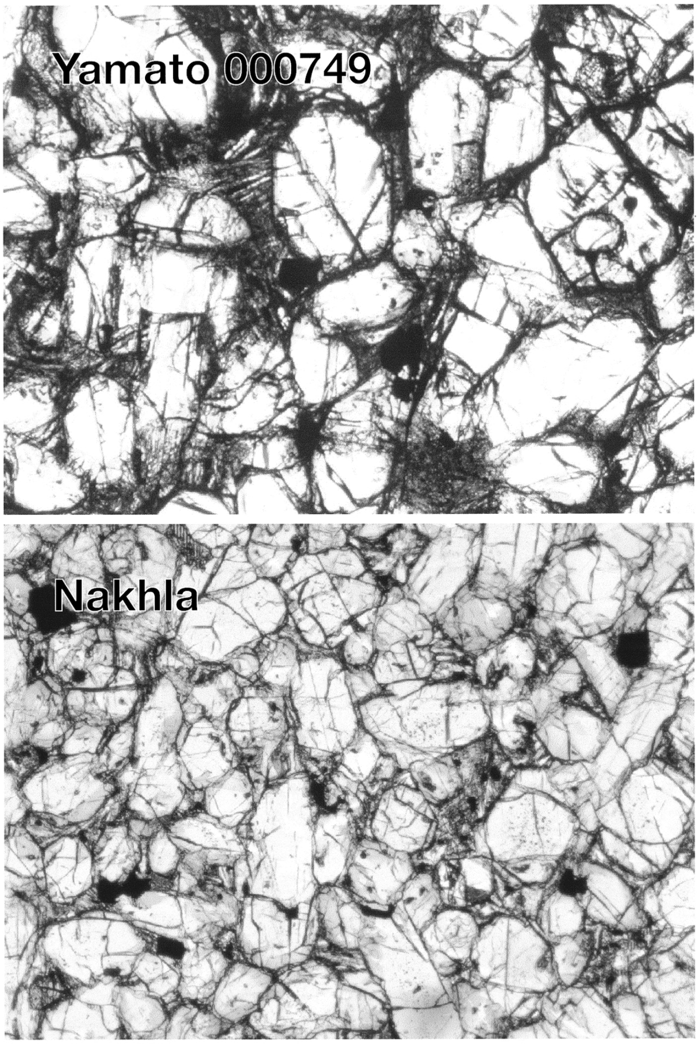

Fig. 5. Photomicrographs thin sections of Yamato 000749,49 and Nakhla. Transmitted light. A field of view is 2.6 mm.

40, confirming literature values of other nakhlites (see Lodders, 1998). Trace element abundances of Y000593 and Y000749 are similar to those of Nakhla. Rare earth element abundance patterns of Y000593 and Y000749 are light REE-rich: CI-chondrite-normalized La/Lu ratio is approximately 4.5 (Oura *et al.,* 2003; Nakamura *et al.,* 2002).

4.3. *Oxygen isotopic signature*

Oxygen isotopic compositions of Y000593 ($\delta^{18}O = +4.84‰$ relative to SMOW, $\delta^{17}O = +2.72‰$, $\Delta^{17}O = +0.203‰$) and Y000749 ($\delta^{18}O = +4.66‰$, $\delta^{17}O = +2.57‰$, $\Delta^{17}O = +0.147‰$) are in agreement with a Martian origin of these meteorites (R.N.

Clayton and T.K. Mayeda, unpublished data, 2001).

4.4. Rare gases and cosmic-ray exposure age

Elemental ratios of trapped $^{36}Ar/^{84}Kr/^{132}Xe$ of the bulk samples of Y000593, Y000749, and Y000802 are identical to those of Nakhla (Okazaki *et al.,* 2003). An averaged CRE age for the three Yamato nakhlites based on cosmogenic ^{21}Ne is calculated to be 12.1 ± 0.7 Ma (Okazaki *et al.,* 2003). The ejection ages of Nakhla, Lafayette, Governador Varadares, NWA817 (Marty *et al.,* 2001), Yamato and the dunite Chassigny are ~ 10 Myr and are the same within experimental errors, suggesting that the all nakhlites and Chassigny were ejected from Mars in a single impact cratering event.

4.5. Rubidium-strontium and samarium-neodymium systematics

Data points of separated mineral and whole-rock fractions from Y000593 define a linear array with a slope corresponding to an Rb-Sr age of ~1.3 Ga (Nakamura *et al.,* 2002; Shih *et al.,* 2002; Misawa *et al.,* 2003). An initial $^{87}Sr/^{86}Sr$ ratio of 0.702525 ± 27 for Y000593 is in good agreement with previous results of Lafayette (Shih *et al.,* 1998) and Chassigny (Nakamura *et al.,* 1982b) but slightly different from those of other nakhlites (Papanastassiou and Wasserburg, 1974; Gale *et al.,* 1975; Shih *et al.,* 1999). The Sm-Nd isotopic system in Y000593 was not disturbed in the six samples (leachates and residues of whole-rock and augite, and one untreated whole-rock sample) analyzed so far. The data define an isochron corresponding to an Sm-Nd age of 1.31 ± 0.03 Ga with an initial $\varepsilon^{143}Nd$ of $+16.0 \pm 0.2$ (Shih *et al.,* 2002; Misawa *et al.,* 2003). The Yamato nakhlites probably crystallized ~1.3 Ga from a low Rb/Sr and light REE-depleted source. The isotopic signatures of the source regions of Antarctic and non-Antarctic nakhlites so far analyzed and Chassigny are identical (Nakamura *et al.,* 1982a; Jagoutz, 1996; Shih *et al.,* 1999; Jagoutz, 2000; see Nyquist *et al.,* 2001).

5. Summary

On the basis of texture, mineralogy, petrology, chemistry, and CRE ages, we conclude that three Yamato nakhlites are paired specimens, bringing the total of identified nakhlites to six. The Yamato nakhlites have many similarities to Nakhla, and, apparently, have escaped from heavy terrestrial weathering, which is sometimes indicated for shergottites and nakhlites found in hot deserts. The Rb-Sr and Sm-Nd ages of Y000593 are ~1.3 Ga and are concordant, showing similar isotopic signatures to those of non-Antarctic nakhlites and Chassigny. These facts strongly suggest that nakhlites and Chassigny crystallized within a short period of time ~1.3 Ga. The ejection ages of nakhlites and Chassigny are ~10 Myr, suggesting that all of the nakhlites and Chassigny were ejected from Mars in a single impact cratering event.

Acknowledgments

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References

Bunch, T.E. and Reid, A.M. (1975): The nakhlites, I. Petrography and mineral chemistry. Meteoritics, **10**, 303–315.

Gale, N.H., Arden, J.W. and Hutchison, R. (1975): The chronology of the Nakhla achondritic meteorite. Earth Planet Sci. Lett., **26**, 195–206.

Gillet, Ph., Barrat, J.A., Deloule, E., Wadhwa, M., Jambon, A., Sautter, V., Devouard, B., Neuville, D., Benzerara, K. and Lesourd, M. (2002): Aqueous alteration in the Northwest Africa 817 (NWA817) Martian meteorite. Earth Planet Sci. Lett., **203**, 431–444.

Gooding, J.L., Wentworth, S.J. and Zolensky, M.E. (1991): Aqueous alteration of the Nakhla meteorite. Meteoritics, **26**, 135–143.

Greshake, A., Stephan, T. and Rost, D. (2000): Combined TEM and TOF-SIMS study of symplectite exsolutions in olivine from the Martian meteorites Nakhla and Governador Valadarez. Lunar and Planetary Science XXXI. Houston, Lunar Planet. Inst., Abstract #1150 (CD-ROM).

Imae, N., Iwata, N. and Shimoda, Y. (2002a): Search for Antarctic meteorites in the bare ice field around the Yamato Mountains by JARE-41. Antarct. Meteorite Res., **15**, 1–24.

Imae, N. Okazaki, R., Kojima, H. and Nagao, K. (2002b): The first nakhlite from Antarctica. Lunar and Planetary Science XXXIII. Houston, Lunar Planet. Inst., Abstract #1438 (CD-ROM).

Imae, N., Ikeda, Y., Shinoda, K., Kojima, H. and Iwata, N. (2003): Yamato nakhlites: Petrography and mineralogy. Antarct. Meteorite Res., **16**, 13–33.

Irving, A.J., Kuehner, S.M., Rumble, D., III, Carlson, R.W., Hupé, A.C. and Hupé, G.M. (2002): Petrology and isotopic composition of orthopyroxene-bearing nakhlite NWA998. Meteorit. Planet. Sci., **37**, Suppl., A70.

Jagoutz, E. (1996): Nd isotopic systematics of Chassigny. Lunar and Planetary Science XXVII. Houston, Lunar Planet. Inst., 597–598.

Jagoutz, E. (2000): New Sm-Nd isotope data on Nakhla minerals. Lunar and Planetary Science XXXI. Houston, Lunar Planet. Inst., Abstract #1609 (CD-ROM).

Kojima, H. and Imae, N., ed. (2001): Meteorite Newsletter, **10** (2), 9 p.

Kojima, H., Nakamura, N., Imae, N. and Misawa, K. (2002): The Yamato nakhlite consortium. Antarctic Meteorites XXVII. Tokyo, Natl Inst. Polar Res., 66–68.

Lodders, K. (1998): A survey of shergottite, nakhlite and chassigny meteorites whole-rock compositions. Meteorit. Planet. Sci., **33**, Suppl., A183–A190.

Marty, B., Marti, K. and Théodore Monod Consortium (2001): Noble gases in new SNC meteorites NWA817 and NWA480. Meteorit. Planet. Sci., **36**, Suppl., A122–A123.

McSween, H.Y., Jr. (1994): What we have learned about Mars from SNC meteorites. Meteoritics, **29**, 757–779.

Mikouchi, T., Yamada, I. and Miyamoto, M. (2000) Symplectic exsolution in olivine from the Nakhla Martian meteorite. Meteorit. Planet. Sci., **35**, 937–942.

Mikouchi, T., Koizumi, E., Monkawa, A., Ueda, Y. and Miyamoto, M. (2003): Mineralogy and petrology of Yamato 000593: Comparison with other Martian nakhlite meteorites. Antarct. Meteorite Res., **16**, 34–57.

Misawa, K., Shih, C.-Y., Wiesmann, H. and Nyquist, L.E. (2003): Crystallization and alteration ages of the Antarctic nakhlite Yamato 000593. Lunar and Planetary Science XXXIV. Houston, Lunar Planet. Inst., Abstract #1556 (CD-ROM).

Nakamura, N., Unruh, D.M., Tatsumoto, M. and Hutchison, R. (1982a): Origin and evolution of the Nakhla meteorite inferred from the Sm-Nd and U-Pb systematics and REE, Ba, Sr, Rb and K abundances. Geochim. Cosmochim. Acta, **46**, 1555–1573.

Nakamura, N., Komi, H. and Kagami, H. (1982b): Rb-Sr isotopic and REE abundances in the Chassigny meteorite. Meteoritics, **17**, 257–258.

Nakamura, N., Yamakawa, A., Yamashita, K., Kobayashi, T., Imae, N., Misawa, K. and Kojima, H. (2002): REE abundances and Rb-Sr age of new Antarctic nakhlite Yamato 000595. Antarctic Meteorites XXVII. Tokyo, Natl Inst. Polar Res., 112–114.

Nyquist, L.E., Bogard, D.D., Shih, C.-Y., Greshake, A., Stöffler, D. and Eugster, O. (2001): Age and geologic histories of Martian meteorites. Chronology and Evolution of Mars, ed. by R. Kallenbach *et al.* Kluwer Academic Publ., 105–164.

Okazaki, R., Nagao, K., Imae, N. and Kojima, H. (2003): Noble gas signatures of Antarctic nakhlites, Yamato (Y) 000593, Y000749, and Y000802. Antarct. Meteorite Res., **16**, 58–79.

Oura, Y., Shirai, N. and Ebihara, M. (2003): Chemical composition of Yamato (Y) 000593 and Y000749: Neutron-induced prompt gamma-ray analysis study. Antarct. Meteorite Res., **16**, 80–93.

Papanastassiou, D.A. and Wasserburg, G.J. (1974): Evidence for late formation and young metamorphism in the achondrite Nakhla. Geophys. Res. Lett., **1**, 23–26.

Russell, S., ed. (2003): The Meteoritical Bulletin, **87–1.**

Sautter, V., Barrat, J.A., Jambon, A., Lorand, J.P., Gillet, Ph., Javoy, M., Joron, J.L. and Lesourd, M. (2002): A new Martian meteorite from Morocco: the nakhlite North West Africa 817. Earth Planet. Sci. Lett., **195**, 223–238.

Shih, C.-Y., Nyquist, L.E., Reese, Y. and Wiesmann, H. (1998): The chronology of the nakhlite, Lafayette: Rb-Sr and Sm-Nd isotopic ages. Lunar and Planetary Science XXIX. Houston, Lunar Planet. Inst., Abstract #1145 (CD-ROM).

Shih, C.-Y., Nyquist, L.E. and Wiesmann, H. (1999): Samarium-neodymium and rubidium-strontium systematics of nakhlite Governador Valadares. Meteorit. Planet. Sci., **34**, 647–655.

Shih, C.-Y., Wiesmann, H., Nyquist, L.E. and Misawa, K. (2002): Crystallization age of Antarctic nakhlite Y000593: Further evidence of nakhlite launch pairing. Antarctic Meteorites XXVII. Tokyo, Natl Inst. Polar Res., 151–153.

Treiman, A.H., Barrett, R.A. and Gooding, J.L. (1993): Preterrestrial aqueous alteration of the Lafayette (SNC) meteorite. Meteoritics, **28**, 86–97.

Treiman, A.H. and Goodrich, C.A. (2002): Pre-terrestrial aqueous alteration of the Y000749 nakhlite meteorite. Antarctic Meteorites XXVII. Tokyo, Natl Inst. Polar Res., 166–167.

Ueda, Y., Miyamoto, M., Mikouchi, T. and Hiroi, T. (2003): Reflectance spectra of the Yamato 000593 nakhlite: Spectroscopic similarities to other nakhlites. Antarct. Meteorite Res., **16**, 94–104.

Yamada, I., Mikouchi, T., Miyamoto, M. and Murakami, T. (1997): Lamella inclusion in olivine from Nakhla (SNC) meteorite. Lunar and Planetary Science XXVIII. Houston, Lunar Planet. Inst., 1597–1598.

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