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The Yamato 980459 olivine-phyric shergottite consortium

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Abstract: Among 4100 meteorite samples found around the Yamato Mountain area during the field season of 1998–1999, Yamato (Y) 980459, weight of 82 g, is identified as a new shergottite. In ordered to improve our knowledge of the shergottite parent body, possibly Mars, a coordinated consortium study of the Y980459 shergottite was organized. Petrological, mineralogical, chemical and isotopic studies revealed that Y980459 is related to the olivine-phyric shergottites and the most primitive Martian basalt so far reported. Y980459 has solidified much faster than other shergottites, as indicated by its lack of plagioclase or maskelynite. Y980459 shows a light REE depleted pattern similar to other "depleted shergottites" Dhofar 019, Dal al Gani (DaG) 476, Sayh al Uhamir (SaU) 005 and Queen Alexandra Range 94201. The Sm-Nd isotopic data suggest that Y980459 crystallized at ~470 Ma and derived from a highly depleted source region. Cosmic-ray exposure age of Y980459 is calculated to be ~1 Ma based on ^{10}Be concentration, which is similar to those of olivine-phyric shergottites DaG 476 and SaU 005. I here present an outline of the consortium and implications for Martian geological history on the basis of ongoing studies.

The first petrographical description of Y980459 by Ansgar Greshake, Jörg Fritz and Dieter Stöffler was not submitted to *Antarctic Meteorite Research*, but to *Geochimica et Cosmochimica Acta* on August 15, 2003, and was published in the May 15, 2004 issue. The other papers concerning Y980459 appeared in the *Antarctic Meteorite Research*, **17** issue are of equal scientific importance and priority.

key words: shergottites, Martian meteorites

1. Introduction

The JARE-39 (1998–1999) wintering over party conducted a meteorite search around the Yamato Mountains area (Kojima *et al*., 2000). Among 4100 meteorites found, Yamato (Y) 980459 was identified as a Martian meteorite, which resembles the olivine-phyric shergottites (Kojima and Imae, 2002; Misawa, 2003). Shergottites are subclassified basaltic, lherzolitic and olivine-phyric (*e.g*., Meyer, 2003; Goodrich, 2003) and show extensive shock features due to impacts. Their crystalline ages are relatively young, 0.17–0.58 Ga (see Nyquist *et al*., 2001). Recently, a total of 8 meteorites, Elephant Moraine 79001 lithology A (EETA 79001A), Dhofar (Dho) 019, Dar al Gani (DaG) 476/489/670/735/876/975/1037, Sayh al Uhamir (SaU) 005/008/051/060/

090/094/120/150, Northwest Africa (NWA) 1068/1110/1183/1775, NWA 1195, NWA 2046 and Y980459, have been thus far identified as olivine-phyric shergottites (Meyer, 2003; Irving *et al*., 2004). Most of the olivine-phyric shergottites were recently recovered from the hot deserts of Oman, Libya and Northwest Africa and some of them were heavily affected by terrestrial contamination. Along with EETA 79001A, Y980459 was found on the bare ice field in Antarctica, and thus enable us to study this type of rock, which is considered to be less affected by terrestrial contamination. The DaG 476 and SaU 005 olivine-phyric shergottites are very similar in mineralogy, chemical compositions and cosmic-ray exposure (CRE) ages of ~1.2 Ma. Dhofar 019 has a significantly older CRE age of ~20 Ma. NWA 1068 has crystallization age similar to basaltic shergottites in the range of ~165–200 Ma and CRE age of ~3 Ma. Systematic studies of olivine-phyric shergottites will provide us new insights into differentiation processes of the Martian mantle and add important new information about Martian volcanism.

After the announcement of this new Antarctic Martian meteorite, more than fifteen sample requests for investigation were received. At a meeting held on 22nd November 2002, the Committee on Antarctic Meteorite Research recognized the need for a coordinated consortium study of the Yamato olivine-phyric shergottite. The goals of this consortium are to identify similarities and differences between Y980459 and other olivine-phyric shergottites, and to constrain chemical and isotopic signatures of the shergottite source(s). The consortium will facilitate a balanced and effective study of the mineralogy, petrology, and geochemistry of this small sample (Misawa, 2003).

2. Yamato 980459 overview

Y980459 was collected on the bare ice field near the Minami-Yamato Nunataks (Fig. 1) on 4th December 1998. The meteorite is a single stone, weighing 82.46 gram, 5.0×4.2×2.6 cm in dimension, and is partially covered with shiny black fusion crust with ablation features (Fig. 2). The surface of the meteorite has been physically eroded and the fusion crust in large part removed (Fig. 2a, c). However, the interior of the rock seems to be fresh (Fig. 2c, d). Olivine is easily identified with the naked eye because of its yellow/orange color. Y980459 is composed of olivine phenocrysts, up to 2 mm in size, pyroxene and abundant interstitial glass (Fig. 3).

3. Curatorial processing of Yamato 980459

Our ongoing plan for the Y980459 consortium is summarized in Table 1. A 90 mg-sized sample (Y980459,70) was allocated to R.N. Clayton (Univ. Chicago) for measurements of oxygen isotopes. Even before the consortium commenced, Y980459,60 (184 mg) was allocated to K. Nagao (Univ. Tokyo) for noble gas study that confirmed Y980459 is a Martian meteorite. In addition to this sample, he received a 248-mg sample (Y980459,66) for trapped noble gas geochemistry. A homogenized powder sample (Y980459,80), weighing 2.585 g, was prepared and an aliquot of 1.4 g (Y980459,81) was used for wet chemical analysis at NIPR (Analyst: H. Haramura). Aliquots of this homogenized sample are available for bulk analysis upon request.

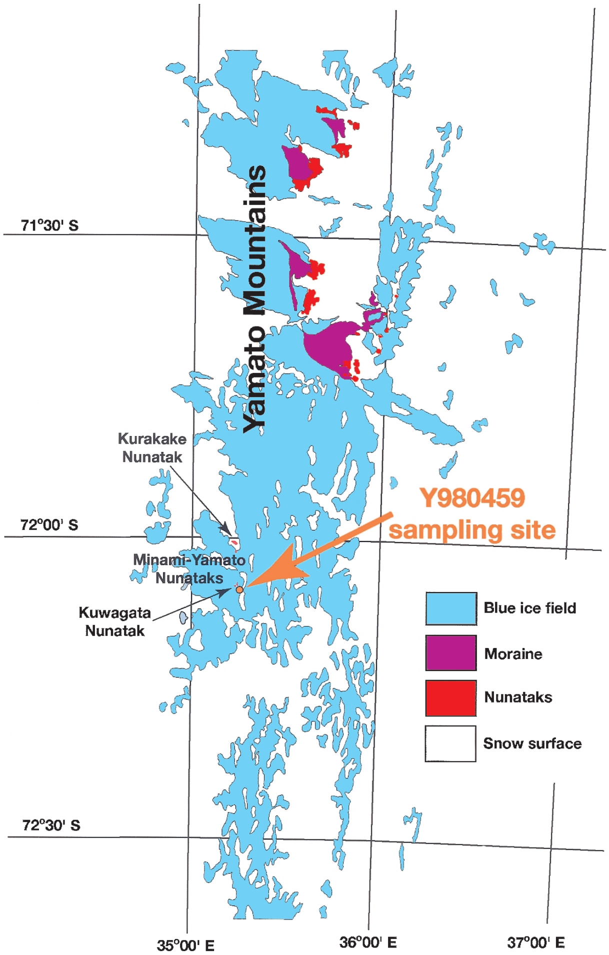

Fig. 1. The sampling site of the Yamato olivine-phyric shergottite. Yamato 980459 was collected at 72°5.881′S, 35°14.559′E, ~2 km south of the Kuwagata-yama Nunatak.

A mass of 308 mg (Y980459,64) was allocated to M. Grady for carbon, nitrogen and oxygen isotope studies. T. Mikouchi (Univ. Tokyo) received a 413-mg sample (Y980459,57) for transmitted electron microscopy (TEM) and for crystallization experiments. D. Stöffler (Humboldt Univ.) received Y980459,75 (231 mg) to study shock effects on the Yamato shergottite by TEM and X-ray diffraction analyses. M. Miyamoto (Univ. Tokyo) received a 108-mg (Y980459,69) sample for reflectance spectroscopy. A fragment weighing 523-mg (Y980459,55) for the Rb-Sr isotope systematics and a 120-mg powdered sample (Y980459,84) for lithophile trace element studies were allocated to N. Nakamura (Kobe Univ.). G. Dreibus (MPI, Mainz) received a 512-mg sample (Y980459,63) for the determination of Rb-Sr, Sm-Nd and U-Pb isotope systematics and a 252-mg powdered sample (Y980459,83) for the determination of trace element abundances with instrumental neutron activation analyses

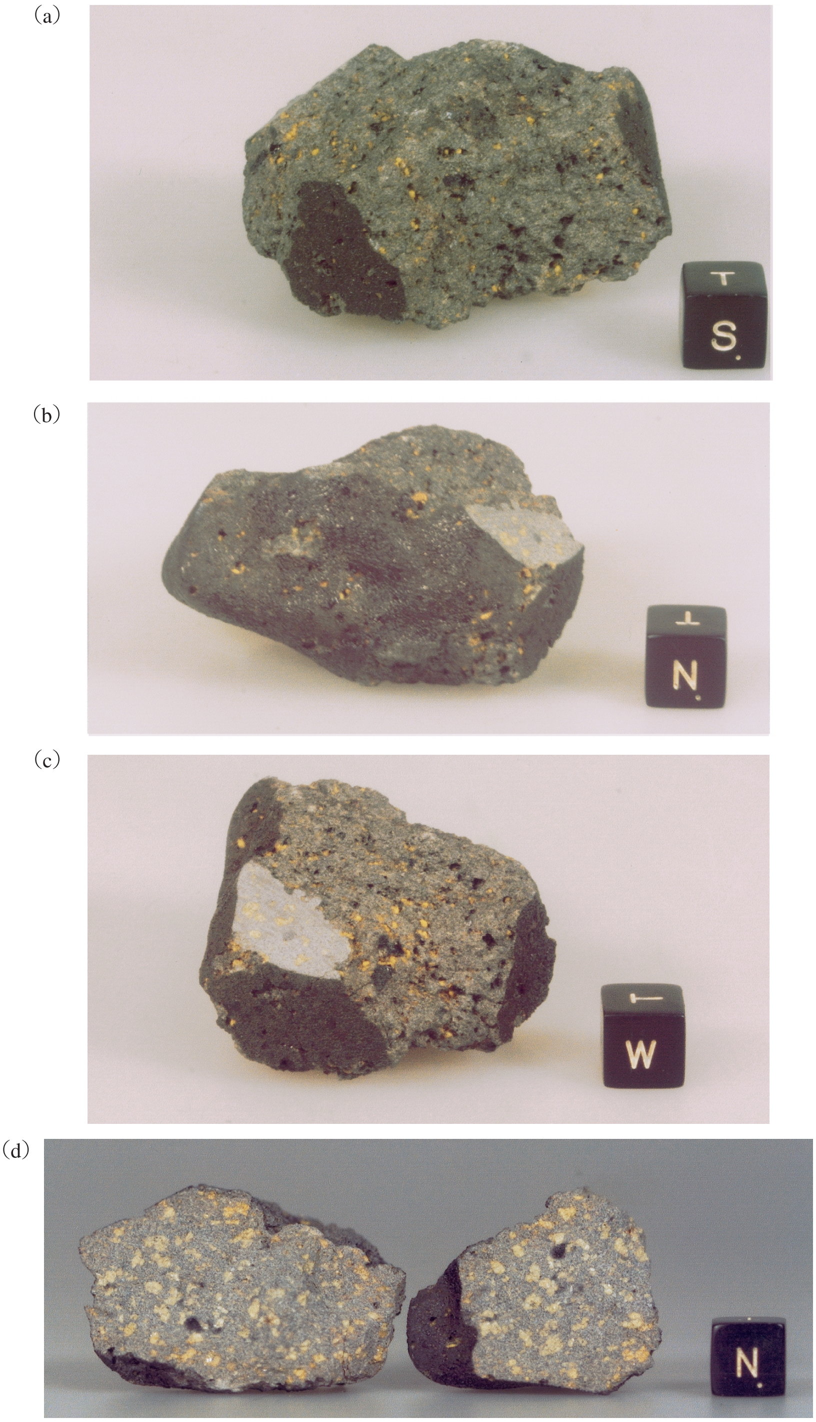

Fig. 2. Macroscopic features (a–c) and cross section (d) of Yamato 980459. The cube is 1 cm^3.

(a)

(a)

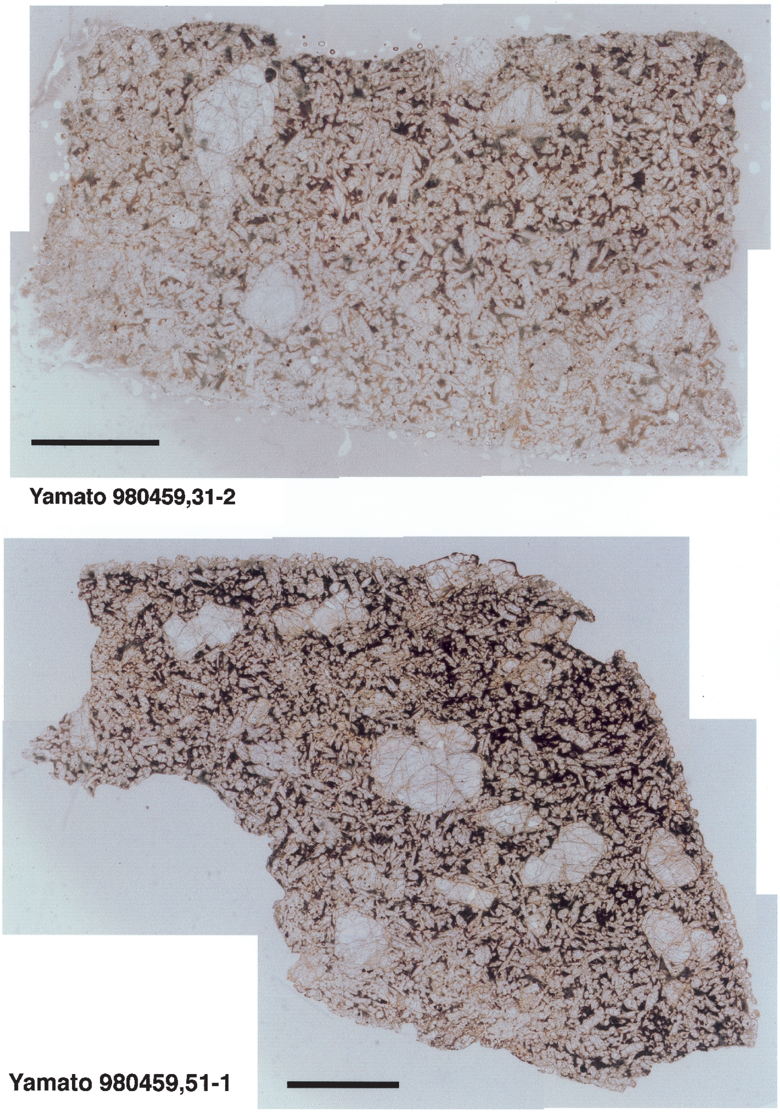

Fig. 3. Photomicrographs of (a) Yamato 980459,31-2 and (b) Yamato 980459,51-1. The meteorite is composed of olivine phenocrysts, up to 2 mm in size, pyroxene and glass with minor amounts of oxide minerals. Scale bar = 2 mm.

(INAA) and radiochemical neutron activation analyses (RNAA). L. Nyquist (NASA-JSC) received fragments weighing a total of 1.487 g. Together with D. Bogard (NASA-JSC) and C.-Y. Shih (Lockheed-Martin), he will determine crystallization age by the Rb-Sr, ^{147}Sm-^{143}Nd and ^{39}Ar-^{40}Ar systems and mantle differention age by the ^{146}Sm-^{142}Nd system. G. McKay (NASA-JSC) received Y980459,54 (783 mg) for Re-Os and ^{146}Sm-^{142}Nd isotope systematics and for investigating shergottite petrogenesis. K. Marti (UCSD) received Y980459,62 (447 mg) for identification of fission, spallation and indigenous components of nitrogen, argon, and xenon in the source region of shergottites. O. Eugster (Univ. Bern) received Y980459,59 (211 mg) for CRE age, parent body ejection time and terrestrial age determinations. In order to study in detail the cosmic-ray effects and pre-atmospheric sizes of Y980459 using ^{41}Ca, ^{36}Cl, ^{26}Al, ^{10}Be and ^{53}Mn, K. Nishiizumi (Space Sci. Lab., UCB) was allocated a 675 mg-sized sample (Y980459,56) containing fusion crust and a 457 mg-sized interior sample (Y980459,60). He will split the interior sample and send aliquots of chips to A. Jull (NSF Arizona AMS Lab., Arizona Univ.) for ^{14}C measurement. V. Hoffman (Univ. Tübingen) received Y980459,65 (506 mg) for studying the magnetic properties of shergottites. Most samples were sent to investigators in February 2003.

Apart from those used for the initial classification (Y980459,31-1, 31-2, and 51-1), twelve polished thin sections (PTSs) were produced for the consortium, from three separate parent chips, Y980459,31, Y980459,41 and Y980459,51 (see Table 1). Thus far, PTSs have been loaned to Y. Ikeda (Ibaraki Univ.), T. Mikouchi (Univ. Tokyo), G. Dreibus (MPI, Mainz), H. McSween (Univ. Tennessee) and G. McKay (NASA-JSC) for mineralogical and petrological studies. Two PTSs, Y980459,41-2 and Y980459,51-2, loaned to G. McKay and to H. McSween, will be used for ion microprobe analysis. M.

Table 1. Distribution of samples for Yamato 980459 Consortium, including PTS samples.

Yamato 9804599 (82.46 gram) Subnumber	Weight (gram)	Investigator	Institution	Type of investigation
31	1.115		NIPR	PTSs
40	1.487	Nyquist, L.	NASA-JSC	chronology
41	1.425		NIPR	PTSs
51	0.950		NIPR	PTSs
54	0.783	McKay, G.	NASA-JSC	petrology & chronology
55	0.523	Nakamura, N.	Kobe Univ.	chronology
56	0.675	Nishiizumi, K.	Space Sci. Lab., UCB	CRE
57	0.413	Mikouchi, T.	Univ. Tokyo	mineralogy & petrology
58	0.457	Nishiizumi, K.	Space Sci. Lab., UCB	CRE
59	0.211	Eugster, O.	Univ. Bern	CRE
60	0.184	Nagao, K.	Univ. Tokyo	noble gases
61	0.231	Stöffler, D.	Inst. Mineralogie, Berlin	shock features
62	0.447	Marti, K.	UCSD	nitrogen & noble gas isotopes
63	0.512	Dreibus, G.	MPI, Mainz	chronology
64	0.308	Grady, M.	NHM, London	stable isotopes
65	0.506	Hoffman, V.	Univ. Tübingen	magnetic property
66	0.248	Nagao, K.	Univ. Tokyo	noble gases
69	0.108	Miyamoto, M.	Univ. Tokyo	reflectance spectroscopy
70	0.092	Clayton, R.	Univ. Chicago	oxygen isotopes
80	2.585		NIPR	powdered sample
81	1.400		NIPR	bulk wet chemistry (from ,80)
82	0.248	Ebihara, M.	Tokyo Metropolitan Univ.	chemistry (from ,80)
83	0.252	Dreibus, G.	MPI, Mainz	chemistry (from ,80)
84	0.120	Nakamura, N.	Kobe Univ.	chemistry (from ,80)

PTSs; Y980459,31-3: Dreibus, G. (MPI, Mainz), Y980459,41-2: McKay, G. (NASA-JSC), Y980459,41-3: Mikouchi, T. (Univ. Tokyo), Y980459,41-5: Ikeda, Y. (Ibaraki Univ.), Y980459,51-2: McSween, H. (Univ. Tennessee), Y980459,41-2: Wadhwa, M. (FMNH).

Wadhwa (FMNH) will study trace and minor element microdistributions of Y980459. In order to estimate the water content of Martian mantle, R. Lenz (Univ. Tennessee) will analyze Li, Be and B contents in pyroxene.

4. Results and discussion

4.1. *Mineralogy and petrology*

Petrographic features of Y980459 are similar to those of olivine-phyric shergottites EETA 79001A, DaG 476, Dho 019, SaU 005, NWA 1068, NWA 1195 and NWA 2046, although NWA 1195 and NWA 2046 also contain orthopyroxene phenocrysts. Mesostasis of Y980459 consists of dendritic olivine, pyroxene, chromite, ilmenite and sulfide but no phosphate (Mikouchi *et al*., 2003, 2004). A noteworthy feature observed in Y980459 is the absence of plagioclase or maskelynite. According to the classical definition, shergottites consist of a somewhat similar Ca-rich pyroxene to that in the eucrites, associated, however, with lath of isotropic maskelynite instead of anorthite (Prior, 1920). The absence of plagioclase is considered to be due to rapid cooling which suppressed nucleation of plagioclase (Greshake *et al*., 2003, 2004; Ikeda, 2003, 2004; McKay and Mikouchi, 2003; Koizumi *et al*., 2004; McKay *et al*., 2004; Mikouchi *et al*., 2004). Although mineral assemblage of Y980459 is different from those of shergottites, Y980459 could be classified as a member of the olivine-phyric shergottite subgroup. As described below, bulk chemical composition of Y980459 supports this. Olivine cores in Y980459 are the most magnesian (Fo_{86}) among shergottites and are almost same as olivine phenocrysts in NWA2046 (Irving *et al*., 2004). Thus, Y980459 is the most primitive olivine-phyric shergottite so far identified.

Shock features are observed in olivine and pyroxene. Shock melt pockets are heterogeneously distributed but they are rare (Ikeda, 2004; Mikouchi *et al*., 2004). Although the lack of plagioclase prevents precise shock pressure estimation, the shock degree of Y980459 is estimated to be 20–25 GPa. (Ikeda, 2004; Greshake *et al*., 2004; Mikouchi *et al*., 2004). Shock pressures of shergottites range from 30–50 GPa (see Nyquist *et al*., 2001). Thus, Y980459 is the least shocked shergottite so far reported.

4.2. *Oxygen isotopic signature*

Oxygen isotopic compositions of Y980459,70 ($\delta^{18}O = +4.31‰$ relative to SMOW, $\delta^{17}O = +2.52‰$, $\Delta^{17}O = +0.28‰$) are in agreement with a Martian origin of Y980459 (R.N. Clayton and T.K. Mayeda, written communication, 2001).

4.3. *Major and trace element composition*

Bulk chemical composition of Y980459 is given in Table 2 together with those of other olivine-phyric shergottites. Bulk *mg* ($=100\times$molar Mg/[Mg+Fe]) values of Y980459, DaG 476 and SaU 005 are ~68, which is higher than those of EETA 79001A, Dho 019, NWA 1068 (*mg*=58–61).

The light REE (LREE) depleted pattern of Y980459 (Dreibus *et al*., 2003; Nakamura *et al*., 2003; Shirai and Ebihara, 2003) is similar to those of olivine-phyric shergottites EETA 79001A (Burghele *et al*., 1983), Dho 019 (Neal *et al*., 2001; Taylor *et al*., 2002), DaG 476 (Ziepfel *et al*., 2000; Barrat *et al*., 2001a), SaU 005 (Dreibus *et

Table 2. Bulk chemical compositions of olivine-phyric shergottites (wt%).

	Y980459*	DaG476 [1, 2]	Dho019 [3]	SaU005 [4]	NWA1068 [5]	EETA 79001A [6]
SiO_2	48.70	45.76		47.20		48.58
TiO_2	0.54	0.39	0.49	0.42	0.77	0.64
Al_2O_3	5.27	4.37	6.65	4.53	5.75	5.37
Cr_2O_3	0.71	0.78	0.50	0.78	0.63	0.59
FeO	17.32	*16.06*	*19.9*	*18.34*	*20.48*	*18.32*
Fe_2O_3	0 **					
MnO	0.52	0.45	0.48	0.46	0.46	0.47
MgO	19.64	19.41	14.6	20.49	16.50	16.31
CaO	6.37	7.66	9.42	5.74	7.91	7.05
Na_2O	0.48	0.51	0.89	0.60	1.14	0.82
K_2O	<0.02	0.038		0.022	0.16	0.03
$H_2O(-)$	0					
$H_2O(+)$	0					
P_2O_5	0.29	0.32	0.4	0.31		0.54
FeS	0.26					
Fe	0					
Ni	0.027	0.0230	0.0065	0.0310		0.0158
Co	0.007	0.0051	0.0045	0.0055		0.0047

* An aliquot of 1.4 gram from the powdered sample (Y980459,81) was used for wet chemical analysis. Analyst: H. Haramura. ** Ferric iron was measured but not detected.
Italics: total iron calculated as FeO. Underline: elemental abundances are significantly affected by terrestrial weathering.
Refs. [1] Barrat *et al.* (2001a), [2] Zipfel *et al.* (2000), [3] Neal *et al.* (2001), [4] Dreibus *et al.* (2000), [5] Barrat *et al.* (2001b), [6] Burghele *et al.* (1983).

al., 2000) and basaltic shergottite QUE 94201 (Dreibus *et al.*, 1996; Warren and Kallemeyn, 1997; Kring *et al.*, 2003). All olivine-phyric shergottites do not necessarily show the LREE depleted pattern: NWA 1068 shows a "flat" REE pattern (Barrat *et al.*, 2001b) similar to those of "enriched" shergottites Shergotty, Zagami, NWA 856 and Los Angeles. These trace element features observed in olivine-phyric shergottites could reflect differences among their source materials. Depleted shergottites (EETA 79001A, Dho 019, DaG 476, SaU 005, QUE 94201 and Y980459) could have derived from primitive, LREE-depleted, reduced source regions and could have been less affected by crustal contamination/assimilation (Shih *et al.*, 1982; Wadhwa, 2001; Herd *et al.*, 2002; Herd, 2003) or by an enriched component in the Martian mantle (Borg *et al.*, 1997).

Terrestrial contamination affected trace elements, especially halogen, alkali and alkaline earth elements in Y980459 (Dreibus *et al.*, 2003; Shih *et al.*, 2003, 2004a). Even though the collected sample-size of QUE 94201 was about one seventh of Y980459, alkaline and alkaline earth elements in QUE 94201 were less affected compared with the case of Y980459. These alteration features observed in Antarctic shergottites imply complicated alteration processes during residence in Antarctica.

4.4. *Noble gases and cosmic-ray exposure age*

Isotopic ratios and concentrations of noble gases were determined for Y980459 (Nagao and Okazaki, 2003; Okazaki and Nagao, 2004). Noble gas abundances in

Y980459 are similar to those of other shergottites. Contribution of Martian atmospheric components, ^{40}Ar and excess of ^{129}Xe, are small. Cosmic-ray exposure ages of Y980459 calculated based on cosmogenic ^{21}Ne and ^{38}Ar are ~2.5 Ma (Okazaki and Nagao, 2004; Christen *et al*., 2004), which is different from those of olivine-phyric shergottites Dho 019 (20 Ma, Shukolyukov *et al*., 2002), EETA 79001A (0.5 Ma, Bogard *et al*., 1984), DaG 476 (1.2 Ma, Zipfel *et al*., 2000), and SaU 005 (1.2 Ma, Pätsch *et al*., 2000) but rather similar to CRE ages of basaltic shergottites QUE 94201 (2.5 Ma, Eugster *et al*., 1997), Shergotty (2.9 Ma, Eugster *et al*., 2002), Zagami (2.85 Ma, Eugster *et al*., 2002), NWA 480 (2.4 Ma, Marty *et al*., 2001) and Los Angels (3.04 Ma, Eugster *et al*., 2002). The CRE age of Y980459 based on ^{10}Be concentration is 1.1 ± 0.2 Ma (Nishiizumi and Hillegonds, 2004), similar to that of olivine-phyric shergottites DaG 476 and SaU 005 but shorter than the CRE ages (~2.5 Ma) based on cosmogenic ^{21}Ne and ^{38}Ar, indicating a significant pre-exposure on the Martian surface (Nishiizumi and Hillegonds, 2004).

4.5. Rubidium-strontium and samarium-neodymium systematics

Shih *et al.* (2003, 2004a, b) studied the Rb-Sr and Sm-Nd isotope systematics of Y980459. It was hard to obtain fractions having wide ranges of Rb/Sr and Sm/Nd due to the lack of plagioclase or maskelynite in Y980459. The Rb-Sr system of Y980459 was "open" and has been severely disturbed by terrestrial weathering even though the sample apparently seems to be fresh. Six samples define a Sm-Nd isochron age of 472 ± 47 Ma with a high initial εNd value of $+36.9 \pm 2.2$ (Shih *et al*., 2004b), identical to values reported for DaG 476 (Borg *et al*., 2003). An initial $^{87}Sr/^{86}Sr$ ratio of 0.701384 ± 0.000011 at 472 Ma is estimated from the weighted average of nine samples (Shih *et al*., 2004b). The Rb-Sr and Sm-Nd isotopic systematics of Y980459, like those of DaG 476 and QUE 94201 (Borg *et al*., 1997, 2003), are consistent with derivation from a source region that was strongly depleted in incompatible elements.

5. Summary

Although plagioclase or maskelynite is absent, Y980459 resembles olivine-phyric shergottites in its petrological featutes and in bulk chemistry. Y980459 is the most primitive Martian basalt so far identified and actually reflects its source region. Y980459 crystallized at 472 ± 47 Ma and derived from a low $^{87}Sr/^{86}Sr$ and a high εNd source region closely related to the source of DaG 476. The ^{10}Be exposure age of Y980459 is 1.1 ± 0.2 Ma, which is similar to those of olivine-phyric shergottites DaG 476 and SaU 005, suggesting a single launching of Y980459 with other olivine-phyric shergottites.

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References

Barrat, J.A., Blichert-Toft, J., Nesbitt, R.W. and Keller, F. (2001a): Bulk chemistry of Saharan shergottite Dar al Gani 476. Meteorit. Planet. Sci., **36**, 23–29.

Barrat, J.A., Jambon, A., Bohn, M., Gillet, Ph., Sautter, V., Göpel, C., Lesourd, M. and Keller, F. (2001b): Petrology and chemistry of the picritic shergottite North West Africa 1068 (NWA 1068). Geochim. Cosmochim. Acta, **66**, 3505–3518.

Bogard, D.D., Nyquist, L.E. and Johnson, P. (1984): Noble gas contents of shergottites and implications for the Martian origin of SNC meteorites. Geochim. Cosmochim. Acta, **48**, 1723–1739.

Borg, L.E., Nyquist, L.E., Taylor, L.A., Wiesmann, H. and Shih, C.-Y. (1997): Constraints on Martian differentiation processes from Rb-Sr and Sm-Nd isotopic analyses of the basaltic shergottite QUE 94201. Geochim. Cosmochim. Acta, **61**, 4915–4931.

Borg, L.E., Nyquist, L.E., Wiesmann, H., Shih, C.-Y. and Reese, Y. (2003): The age of Dar al Gani 476 and the differentiation history of the martian meteorites inferred from their radiogenic isotopic systematics. Geochim. Cosmochim. Acta, **67**, 3519–3536.

Burghele, A., Dreibus, G., Palme, H., Rammensee, W., Spettel, B., Weckwerth, G. and Wänke, H. (1983): Chemistry of shergottites and the shergotty parent body (SPB): Further evidence for the two component model of planet formation. Lunar and Planetary Science XIX. Houston, Lunar Planet. Inst., 80–81.

Christen, F., Busemann, H., Lorenzetti, S. and Eugster, O. (2004) Mars-ejection ages of Y000593, Y000749, and Y000802 (paired nakhlites) and Y980459 shergottite. Antarctic Meteorites XXVIII. Tokyo, Natl Inst. Polar Res., 6–7.

Dreibus, G., Spettel, B., Wlotzka, F., Schultz, L., Weber, H.W., Jochum, K.P. and Wänke, H. (1996): QUE 94201: An unusual Martian basalt. Meteorit. Planet. Sci., **31**, A39–A40.

Dreibus, G., Spettel, B., Haubold, R., Jochum, K.P., Palme, H., Wolf, D. and Zipfel, J. (2000): Chemistry of a new shergottite: Sayh al Uhaymir 005. Meteorit. Planet. Sci., **35**, A49.

Dreibus, G., Haubold, R., Huisl, W. and Spettel, B. (2003): Comparison of the chemistry of Yamato 980459 with DaG 476 and SaU 005. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 19–20.

Eugster, O., Weigel, A. and Polnau, E. (1997): Ejection times of Martian meteorites. Geochim. Cosmochim. Acta, **61**, 2749–2757.

Eugster, O., Busemann, H., Lorenzetti, S. and Terribilini, D. (2002): Ejection ages from ^{81}Kr-^{83}Kr dating and pre-atmospheric sizes of Martian meteorites. Meteorit. Planet. Sci., **37**, 1345–1360.

Goodrich, C.A. (2003): Petrogenesis of olivine-phyric shergottites Sayh al Uhaymir 005 and Elephant Moraine A79001 lithology A. Geochim. Cosmochim. Acta, **67**, 3735–3771.

Greshake, A., Fritz, J. and Stöffler, D. (2003): Petrography and shock metamorphism of the unique shergottite Yamato 980459. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 29–30.

Greshake, A., Fritz, J. and Stöffler, D. (2004): Petrology and shock metamorphism of the olivine-phyric shergottite Yamato 980459: Evidence for a two-stage cooling and a single-stage ejection history. Geochim. Cosmochim. Acta, **68**, 2359–2377.

Herd, C.D.K. (2003): The oxygen fugacity of olivine-phyric martian basalts and the components within the mantle and crust of Mars. Meteorit. Planet. Sci., **38**, 1793–1805.

Herd, C.D.K., Borg, L.E., Jones, J.H. and Papike, J.J. (2002): Oxygen fugacity and geochemical variations in the Martian basalts: Implications for Martian basalt petrogenesis and the oxidation state of the upper mantle of Mars. Geochim. Cosmochim. Acta, **66**, 2025–2036.

Ikeda, Y. (2003): Petrology of the Yamato 980459 shergottite. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 42.

Ikeda, Y. (2004): Petrology of the Yamato 980459 shergottite. Antarct. Meteorite Res., **17**, 35–54.

Irving, A.J., Bunch, T.E., Kuehner, S.M. and Wittke, J.H. (2004): Petrology of primitive olivine-orthopyroxene-phyric shergottites NWA2046 and NWA1195: Analogies with terrestrial boninites and implications for partial melting of hydrous Martian mantle. Lunar and Planetary Science XXXV. Houston, Lunar Planet. Inst., Abstract #1444 (CD-ROM).

Koizumi, E., Mikouchi, T., McKay, G., Monkawa, A., Chokai, J. and Miyamoto, M. (2004): Yamato 980459: Crystallization of Martian magnesian magma. Lunar and Planetary Science XXXV. Houston, Lunar Planet. Inst., Abstract #1494 (CD-ROM).

Kojima, H. and Imae, N. (2002): Meteorite Newslett., **11** (1), 49 p.

Kojima, H., Kaiden, H. and Yada, T. (2000): Meteorite search by JARE-39 in 1998–1999 season. Antarct. Meteorite Res., **13**, 1–8.

Kring, D.A., Gleason, J.D., Swindle, T.D., Nishiizumi, K., Caffee, M.W., Hill, D.H., Jull, A.J.T. and Boynton, W.V. (2003): Composition of the first bulk melt sample from a volcanic region of Mars: Queen Alexandra Range 94201. Meteorit. Planet. Sci., **38**, 1833–1848.

Marty, B., Marti, K. and Théodore Monod Consortium (2001): Noble gases in new SNC meteorites NWA817 and NWA 480. Meteorit. Planet. Sci., **36**, A122–A123.

Meyer, C. (2003): Mars Meteorite Compendium - 2003. http://www-curator.jsc.nasa.gov/curator/antmet/mmc/mmc.htm.

McKay, G. and Mikouchi, T. (2003): Crystallization of Antarctic shergottite Yamato 980459. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 76–77.

McKay, G., Le, L., Schwandt, C., Mikouchi, T., Koizumi E. and Jones, J. (2004): Yamato 980459: The most primitive shergottite? Lunar and Planetary Science XXXV. Houston, Lunar Planet. Inst., Abstract #2154 (CD-ROM).

Mikouchi, T., Koizumi, E., McKay, G., Monkawa, A., Ueda, Y. and Miyamoto, M. (2003): Mineralogy and petrology of the Yamato 980459 martian meteorite: A new shergottite-related rock. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 82–83.

Mikouchi, T., Koizumi, E., McKay, G., Monkawa, A., Ueda, Y., Chokai, J. and Miyamoto, M. (2004): Yamato 980459: Mineralogy and petrology of a new shergottite-related rock from Antarctica. Antarct. Meteorite Res., **17**, 13–34.

Misawa, K. (2003): The Yamato 980459 shergottite consortium. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 84–85.

Nagao, K. and Okazaki, R. (2003): Noble gases of Y980459 shergottite. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 94.

Nakamura, N., Kobayashi, T. and Yamashita, K. (2003): REE abundances and Rb-Sr systematics of the Yamato 980459 shergottite: A progress report. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 99.

Neal, C.R., Taylor, L.A., Ely, J.C., Jain, J.C. and Nazarov, M.A. (2001): Detailed geochemistry of new Shergottite, Dhofar 019. Lunar and Planetary Science XXXII. Houston, Lunar Planet. Inst., Abstract #1671 (CD-ROM).

Nishiizumi, K. and Hillegonds, D.J. (2004) Exposure and terrestrial histories of new Yamato lunar and Martian meteorites. Antarctic Meteorites XXVIII. Tokyo, Natl Inst. Polar Res., 60–61.

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. and Nagao, K. (2004): Noble gases of Yamato 980459 shergottite. Antarct. Meteorite Res., **17**, 68–83.

Pätsch, M., Altmaier, M., Herpers, U., Kosuch, H., Michel, R. and Schultz, L. (2000): Exposure age of the new SNC meteorite Sayh al Uhaymir 005. Meteorit. Planet. Sci., **35**, A124–A125.

Prior, G.T. (1920): The classification of meteorites. Mineral. Mag., **19**, 51–63.

Shih, C.-Y., Nyquist, L.E., Bogard, D.D., McKay, G.A., Wooden, J.L., Bansal, B.M. and Wiesmann, H.

(1982): Chronology and petrogenesis of young achondrites, Shergotty, Zagami, and ALHA77005: Late magmatism on a geologically active planet. Geochim. Cosmochim. Acta, **46**, 2323–2344.

Shih, C.-Y., Nyquist, L.E. and Wiesmann, H. (2003): Isotopic studies of Antarctic olivine-phyric shergottite Y980459. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 125–126.

Shih, C.-Y., Nyquist, L.E., Wiesmann, H. and Misawa, K. (2004a): Rb-Sr and Sm-Nd isotopic studies of shergottite Y980459 and a petrogenetic link between depleted shergottites and nakhlites. Lunar and Planetary Science XXXV. Houston, Lunar Planet. Inst., Abstract #1814 (CD-ROM).

Shih, C.-Y., Nyquist, L.E., Wiesmann, H. and Misawa, K. (2004b): Rb-Sr and Sm-Nd dating of olivine-phyric shergottite Y980459: Petrogenesis of depleted shergottites. submitted to Antarct. Meteorite Res., **18**.

Shirai, N. and Ebihara, M. (2003): Chemical composition of Yamato 980459. International Symposium—Evolution of Solar System Materials: A New Perspective from Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 127–128.

Shukolyukov, Yu.A., Nazarov, M.A. and Schultz, L. (2002): A new Martian meteorite: the Dhofar 019 shergottite with an exposure age of 20 million years. Solar System Res., **36**, 125–135.

Taylor, L.A., Nazarov, M.A., Shearer, C.K., Lents, R.C., Clayton, R.N. and Mayeda, T.K. (2002): Martian meteorite Dhofar 019: a new shergottite. Meteorit. Planet. Sci., **37**, 1107–1128.

Wadhwa, M. (2001): Redox state of Mars' upper mantle and crust from Eu anomalies in shergottite pyroxenes. Science, **291**, 1527–1530.

Warren, P.H. and Kallemeyn, G.W. (1997): Yamato-793605, EET79001 and other presumed Martian meteorites: Compositional clues to their origins. Antarct. Meteorite Res., **10**, 61–81.

Zipfel, J., Scherer, P., Spettel, B., Dreibus, G. and Schultz, L. (2000): Petrology and chemistry of the new shergottite Dar al Gani 476. Meteorit. Planet. Sci., **35**, 95–106.