Reference List

Yamato 000593 – 13.7 kilograms
Y000749 – 1.28 kilograms
Y000802 – 22 grams
Nakhlite

Figure 1. *Photograph of Y000593 kindly provided by Paul Buchanan, NIPR. Per observation by Mike Zolensky, this is a view of the "least weathered side." Tiny cube is 1 cm (for scale).*

Introduction

Yamato 000593 (13.7 kg), Y000749 (1.28 kg) and Y000802 (22 g) are paired specimens of the first nakhlite found in Antarctica by JARE* (Imae *et al*. 2002). About 60% of the surface of Y000593 is covered with a black fusion crust (figure 1). The reverse side is badly eroded, probably by blowing snow and freeze/thaw cycles.

This sample has been studied by a coordinated consortium led by Keiji Misawa (2003). The age has been determined as 1.3 b.y., with exposure to cosmic rays 11 – 12 m.y.

* *footnote:* altogether, JARE41 found 3550 meteorites during the 2000-2001 field season !

Petrography

As with the other nakhlites, Y000593 and Y000749 are unbrecciated cumulus igneous rocks. Imae *et al.* (2002, 2003) reported that a thin section of Y000593 shows that the sample mainly consists of coarse-grained elongated augite crystals (1 mm x 0.5 mm). Accessory minerals include olivine and opaques; mesostasis includes plagioclase, pyrrhotite, apatite, fayalite, tridymite and magnetite (figure 2). The samples appear similar to Nakhla and only lightly shocked (figure 3 a,b).

As is the case with other nakhlites, Y000749 and Y000593 also have evidence of pre-terrestrial alteration (on Mars!). Some of the alteration material in Y000749 is melted near the fusion crust, "proving" its extraterrestrial origin (Treiman and Goodrich 2002). The existence of bubbles in an OH-bearing phase in olivine grains in contact with the fusion crust suggests

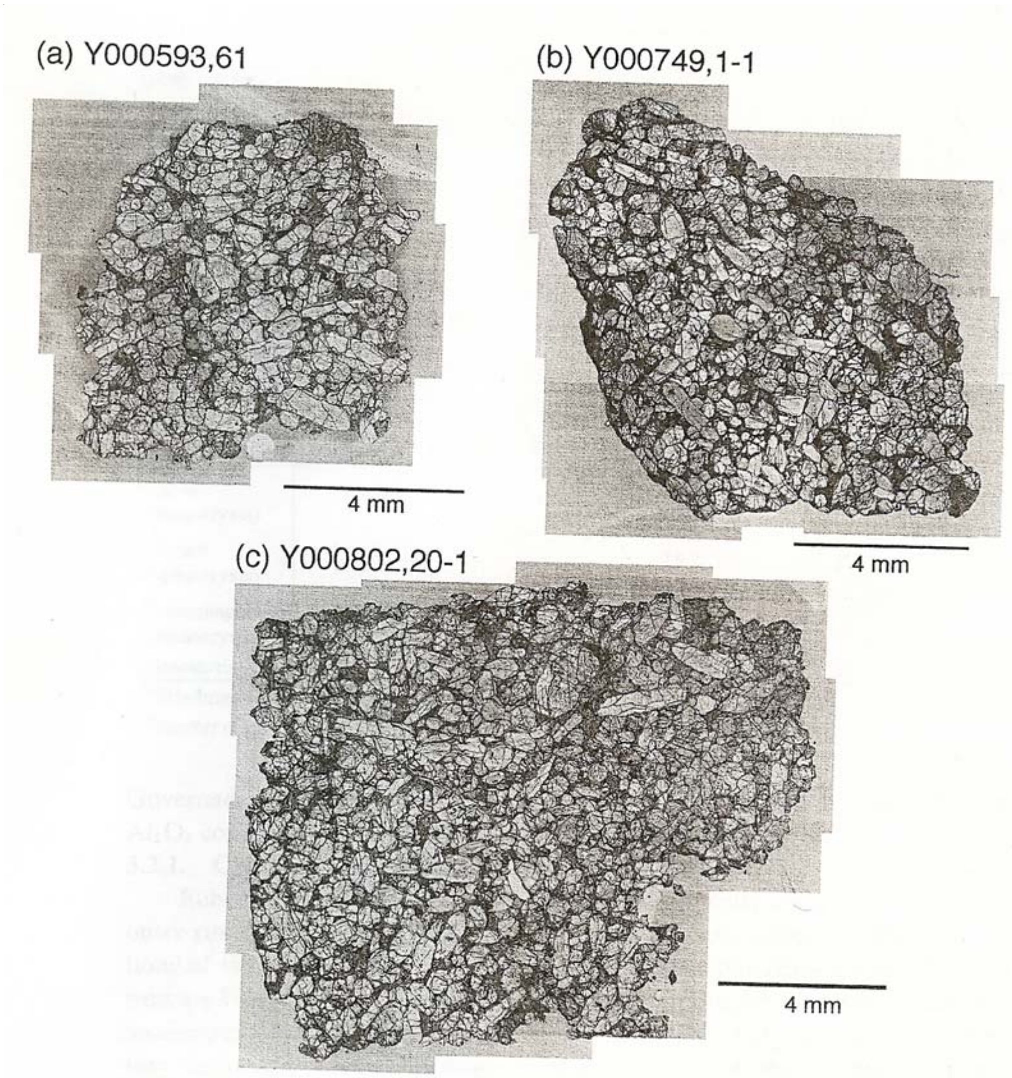

Figure 2: *Low magnification photomicrographs of thin sections of Yamato nakhlite specimens (from Imae et al. 2003).*

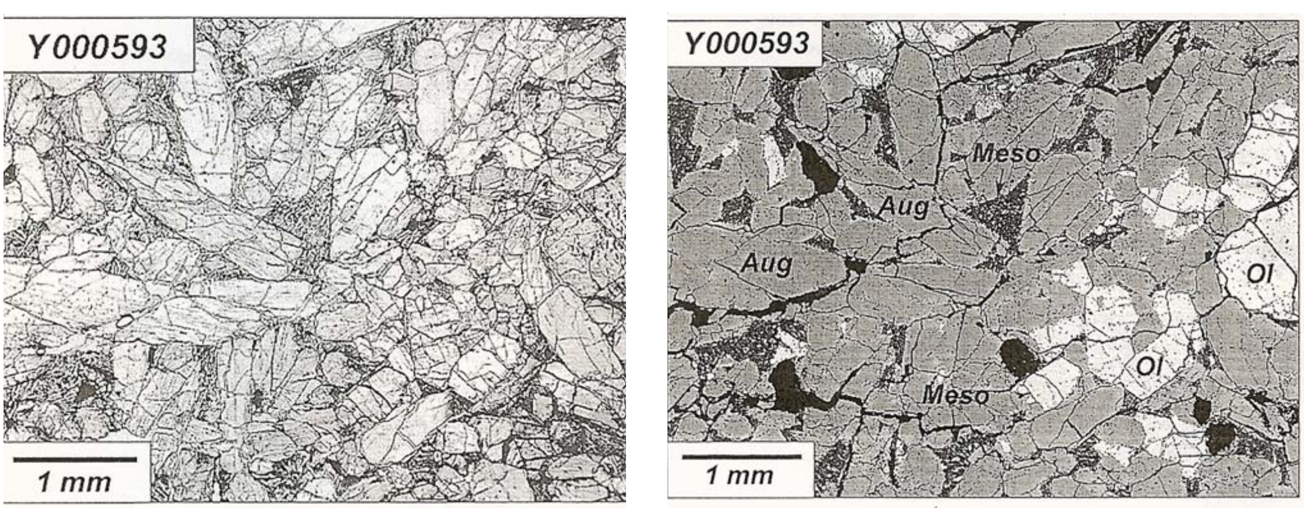

Figure 3 a, b: *Higher magnification photos of Y000593 (optical and back scattered electron) of same region (from Mikouchi et al. 2003).*

that the alteration occurred before atmospheric entry (Imae *et al.* 2003).

Mikouchi *et al.* (2003) provide a nice comparison of the various nakhlites. They find that Y000593 has a cooling rate and depth of burial most similar to that of Nakhla and intermediate of that of NWA817 and Lafayette.

Mineral Chemistry

Pyroxenes: The composition of pyroxene is roughly $En_{70-50}Wo_{35}$ (figure 4). The augite crystals are euhedral and elongate, up to 1.5 mm, and show polysynthetic twinning (Mikouchi *et al.* 2002). The chemical composition of the augite cores closely matches that of the other nakhlites (Misawa *et al.* 2003).

Olivine: Olivine (Fo_{22-38}) is found interstitial to augite (Mikouchi *et al.* 2003, Imae *et al.* 2003).

Plagioclase: Thin plagioclase laths in the mesostasis (roughly An_{30}) are crystalline and intergrown with silica and ternary feldspar (or glass?) (*see* fig. 8 of Imae *et al.* 2003).

"Iddingsite": Alteration is found as thin veinlets in olivine and as replacement for mesostasis in of thin section of Y000749 (Treiman and Goodrich 2002). In veinlets, the alteration material is found to be optically and chemically zoned parallel to veinlet walls *(see also section on alteration in chapter III)*. Fourier transform infrared microspectrometer shows that iddingsites in olivine fractures and in mesostasis consist of 30% goethite and 70% montmorillonite (Imae *et al.* 2003).

Magnetite: Magnetite is Ti-rich with phenopcrysts up to 300 microns. Exsolution of thin ilmenite lamellae is present (Imae *et al.* 2003).

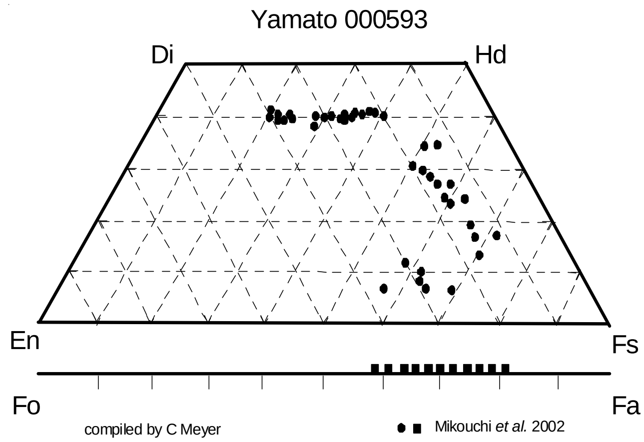

***Figure 4**: Pyroxene and olivine composition diagram for Yamato 000593 (data replotted from Mikouchi et al. 2002).*

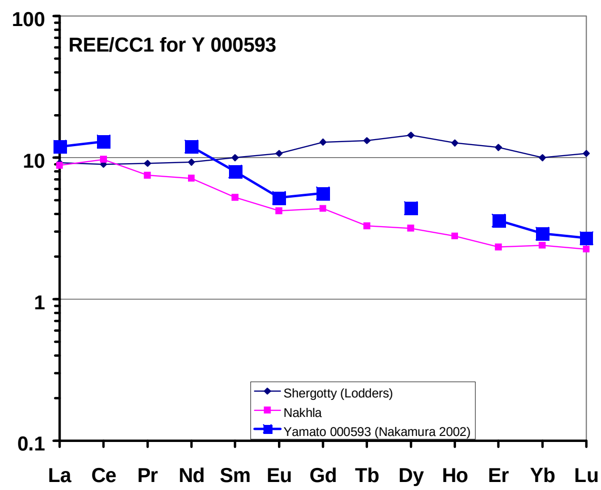

***Figure 5**: Normalized rare earth element diagram comparing data from Yamato 000593 with Nakhla and Shergotty (data from Nakamura et al. 2002).*

Mineralogical Mode

	Mikouchi *et al. (2002)*	Mikouchi *et al. (2003)*	Imae 2003
Pyroxene	85 vol. %	80	76.7
Olivine	10	10	12.2
Opaque			0.6
Mesostasis	5	10	10.5

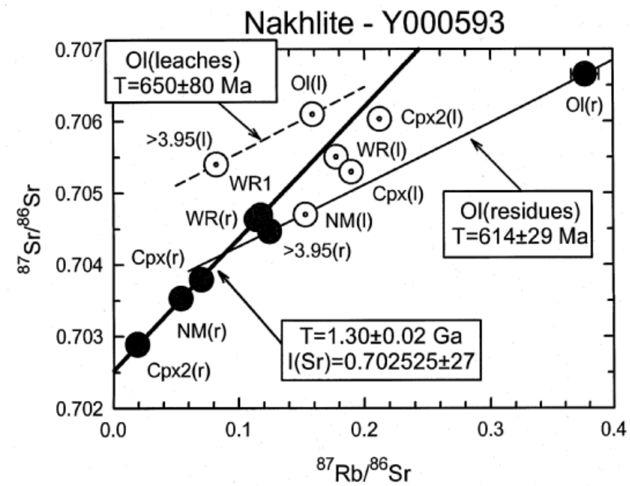

Figure 6: Rb-Sr isochron diagram for Y000593 (data from Misawa et al. 2003).

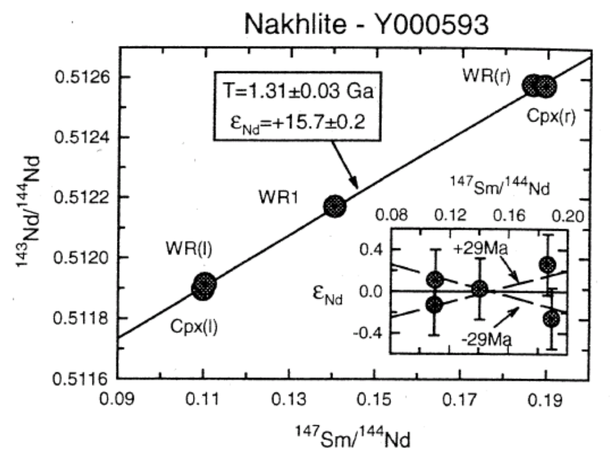

Figure 7: Sm-Nd isochron for Y000593 (data from Shih et al. 2002).

Symplectite: Olivine in the Yamato nakhlite contains magnetite-augite symplectite exsolutions.

Tridymite: Imae *et al.* (2003) note the presence of trace amount of silica (proven tridymite by Nakamuta with Gandolfi camera).

Sulfide: The sulfide in Y00593 has been identified as pyrrhotite ($Fe_{0.86-0.88}S$) (Imae *et al.* 2003).

Whole-rock Composition

The compositions of Y000593 and Y000749 have been reported by Imae *et al.* (2003), Oura *et al.* (2002, 2003), Shirai *et al.* (2002), Dreibus *et al.* (2003) and Nakamura *et al.* (2002) (table 1, figure 5). The wet chemical analysis by Haramura (2003) (reported in Imae *et al.* 2003) showed about 2 % Fe_2O_3. Imae *et al.* note that Y000593 has slightly higher Al than the other nakhlites.

Oura *et al.* have developed a procedure to get the H contents of "lump" samples (Y000593 = 0.05 % H).

Radiogenic Isotopes

Shih *et al.* (2002) reported a Rb-Sr isochron 1.30 ± 0.03 b.y. (figure 6) and a Sm-Nd isochron 1.31 ± 0.03 b.y. (figure 7). Nakamura *et al.* (2002) reported a Rb-Sr isochron of 1.269 ± 0.240 b.y. Okazaki *et al.* (2003) determined the K-Ar age as 1.24 ± 0.22 b.y.

Cosmogenic Isotopes

Imae *et al.* (2002) determined cosmic ray exposure ages; 13.1 m.y. from ^{3}He, 11.3 from ^{21}Ne, and 8.7 m.y. from ^{38}Ar, which are typical of the nakhlites. Okazaki *et al.* (2002) reported 13.23, 12.16 and 7.83 m.y., respectively. The ^{81}Kr age for Y000593 measured as 11.8 ± 1.0 m.y. by Okazaki *et al.* (2003), is consistent with the average ^{21}Ne age of 12.05 ± 0.69 m.y. and indicates a short terrestrial exposure age. Okazaki conclude that the Mars ejection age is 12.1 ± 0.7 m.y.

Other Isotopes

Imae *et al.* (2002) determined Kr, Xe and Ar isotopes at various release temperatures (on sample Y000749) and found that the 1300°C fraction plotted "on a mixing line between Chassigny and iddingsite for Nakhla". Xenon isotopes are mixtures of Chassigny Xe, fission Xe and Mars atmosphere (Okazaki *et al.* 2003).

Pb isotopes were reported by Yamashita *et al.* (2002).

The oxygen isotope composition of Y000593 is ä^{18}O = +4.84‰, ä^{17}O = +2.72‰ and Ä^{17}O = + 0.203‰, and for Y000749 it is ä^{18}O = +4.66‰, ä^{17}O = +2.57‰ and Ä^{17}O = + 0.147‰ per analysis by Clayton and Mayeda (as reported in Misawa *et al.* 2003).

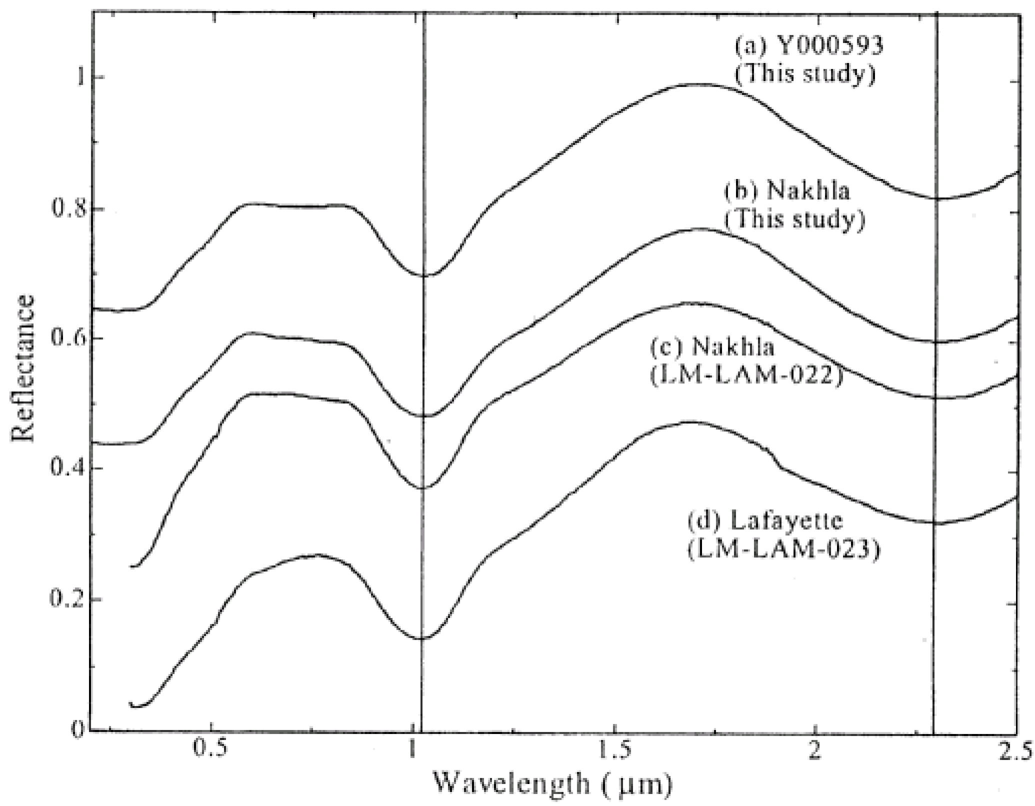

Figure 8. *Reflectance spectra for nakhlites (figure 2 in Ueda et al. 2003). Y000593 and Nakhla from Ueda et al. 2003; Nakhla and Lafayette by McFadden; all with 30 deg incident and 0 deg emergence; all at Brown Univ. RELAB facility.*

Other studies

Magnetic properties of Y000593 were reported by Funaki *et al*. (2002). Reflectance spectra of Y00593 were obtained by Ueda *et al*. (2002, 2003) and compared with other nakhlites (figure 8).

Processing

This large nakhlite is being studied by the Yamato Nakhlite Consortium (Kojima *et al.* 2002). The details of sample splitting and allocation distribution are described in Kojima *et al.* (2002) and Misawa *et al.* (2003). About 61 grams and 15 thin sections of Y000593 were made available for initial studies of Y000593.

A homogeneous powder (15 g) has been prepared from 6 randomly selected chips (Misawa *et al.* 2003).

References for Yamato 000593, 749 and 802

Table 1: Chemical Composition of Y000593.

						749			749			
reference	Oura 2002		Shirai 2002		Dreibus03	Dreibus03	Imae 03	Haramura	Haramura		Oura 03	
weight			12 grams					2.18 g	2.014 g		6 x .1 g	
SiO2			47.57	(a)			48.35	47.93	48.77	(c)	47.6	(b)
TiO2			0.29	(a)			0.47	0.47	0.46	(c)	0.41	(b)
Al2O3			1.88	(a)			1.96	1.91	2.01	(c)	2	(b)
FeO *			19.67	(a)	21.01	22.41	21.35	21.71	21.16	(c)	22.4	(b)
MnO			0.51	(a)	0.513	0.52	0.59	0.59	0.58	(c)	0.52	(b)
CaO			14.27	(a)	13.7	13.7	14.9	14.71	15.08	(c)	14.3	(b)
MgO			10.39	(a)			11.09	11.1	11.08	(c)	10.2	(b)
Na2O			0.58	(a)	0.643	0.593	0.66	0.64	0.68	(c)	0.71	(b)
K2O			0.14	(a)			0.17	0.18	0.16	(c)	0.16	(b)
P2O5			0				0.21	0.29	0.13	(c)		
sum			95.3					100.05	100.5			
Li ppm					4.6							
B	3.47	(b)	3.47	(a)							3.64	(b)
Cl	53	(b)	52.9	(a)	101						120	(b)
Sc					58.2	57.8						
V												
Cr	1790	(b)	1790	(a)				1642	1915	(c)	2100	(b)
Co	91	(b)	91	(a)	43.9	49.1					110	(b)
Ni	179	(b)	179	(a)	56	72						
Cu												
Zn					89	105						
Ga					3.8	3.9						
Ge												
As												
Se												
Br					0.078	0.26						
Rb					4	4						
Sr					90	100						
Y												
Zr												
Nb												
Mo												
I ppm					0.378							
Cs ppm					0.36	0.34						
Ba					32	40						
La					2.79							
Ce					7.41							
Pr												
Nd					4.19	4.26						
Sm	1.46	(b)	1.46	(a)	1.095	1.09					1.6	(b)
Eu					0.325	0.317						
Gd	1.17	(b)	1.17	(a)							1.1	(b)
Tb					0.16	0.16						
Dy					1.1	0.99						
Ho					0.22	0.21						
Er												
Tm												
Yb					0.46	0.455						
Lu					0.076	0.076						
Hf					0.4	0.38						
Ta					0.115	0.105						
W ppb					300	200						
Re ppb												
Os ppb												
Ir ppb												
Au ppb					2.6	1.9						
Tl ppb												
Th ppm					0.23	0.22						
U ppm					0.055	0.058						

technique: (a) INAA and IPAA, (b) PGA, (c) wet chem.

* note: FeO recalculated from FeO, Fe2O3 and FeS