Reference List

MIL 03346 – 715.2 grams
MIL090030 – 452.6 grams
MIL090032 – 532.5 grams
MIL090136 – 171 grams
Nakhlite

Figure 1: *MIL03346 on ice "let's come back next year and look for the rest of it".*

Introduction

The NASA Mars Exploration Program supplemented the 2003-2004 ANSMET expedition in the hope of improving the chance of finding additional samples of Mars, and, as luck would have it, a large nakhlite was recovered from the blue ice on Dec 15, 2003 in the Miller Range, among the other 1358 new specimens discovered during this field season (Satterwhite and Righter 2004). http://geology.cwru.edu/~ansmet/

About 60 % of the surface of MIL 03346 was covered with a black, wrinkled fusion crust (figure 2). MIL 03346 is a nakhlite with abundant clinopyroxene and rare olivine set in a fine-grained mesostasis with some alteration (figure 3). It is apparently part of the same lava flow as the other nakhlites, but has had a faster cooling history (Day *et al.* 2006). It has a high proportion of glassy mesostasis, with some pre-terrestrial alteration.

But that's not all. The 2009 ANSMET team returned three additional samples of the very same Nakhlite (figure 3b).

MIL03346 has been measured as 1.3 to 1.4 b.y. old, and has an exposure to cosmic rays of ~ 10 m.y.

Petrography

MIL 03346 (MIL for short) is a cumulate of abundant elongate clinopyroxene (0.2 to 2.5 mm) and minor olivine crystals (up to 1.7 mm) set in a dark-colored, fine-grained intercumulate mesostasis (Stopar *et al.* 2005; McKay and Schwandt 2005; Mikouchi *et al.* 2005; Rutherford *et al.* 2005; Day *et al.* 2006 and Imae and Ikeda 2007). Stopar *et al*. and Day *et al.* compared

Figure 2: Closeup photo of MIL 03346.

the grain size distribution of MIL with that of the other clinopyroxenites, finding that it had the largest average crystal size (0.43 x 0.26 mm).

Magmatic melt inclusions are reported in the olivine (Rutherford *et al*. 2005) and in augite (Imae and Ikeda 2007). Various phases, including jarosite, saponite and Cl-rich amphibole, have been reported in these melt inclusions (McCubbin *et al.* 2008; Imae and Ikeda 2007; Sauter *et al.* 2006). Imae and Ikeda calculate the composition of the trapped (parental) magma from these melt inclusions.

The mesostasis (figure 5) consists of a dendritic intergrowth of fayalite, ferro-heddenbergite, Ti-magnetite, cristobalite, apatite and feldspar glass (similar to that of NWA 817). No plagioclase has been found in MIL. Day *et al.* (2005, 2006) conclude that MIL is part of the same cumulate-rich lava flow as the other nakhlites, but that it experienced less equilibration and faster cooling than the other nakhlites.

Olivine has "iddingsite-smectite"(?) alteration in cracks, similar to that found in the other nakhlites (Arnand *et al.* 2005; Stopar *et al.* 2005). Mikouchi *et al*. (2005) note that the alteration in MIL 03346 (Antarctica) is similar to that in NWA 817 (Sahara

Figure 3: Thin section photomicrograph of MIL03346. Scale bar is 1 mm. Euhedral clinopyroxene is set in fine-grained mesostasis (opaque). Areas of apparent alteration are present. Photo is from newsletter.

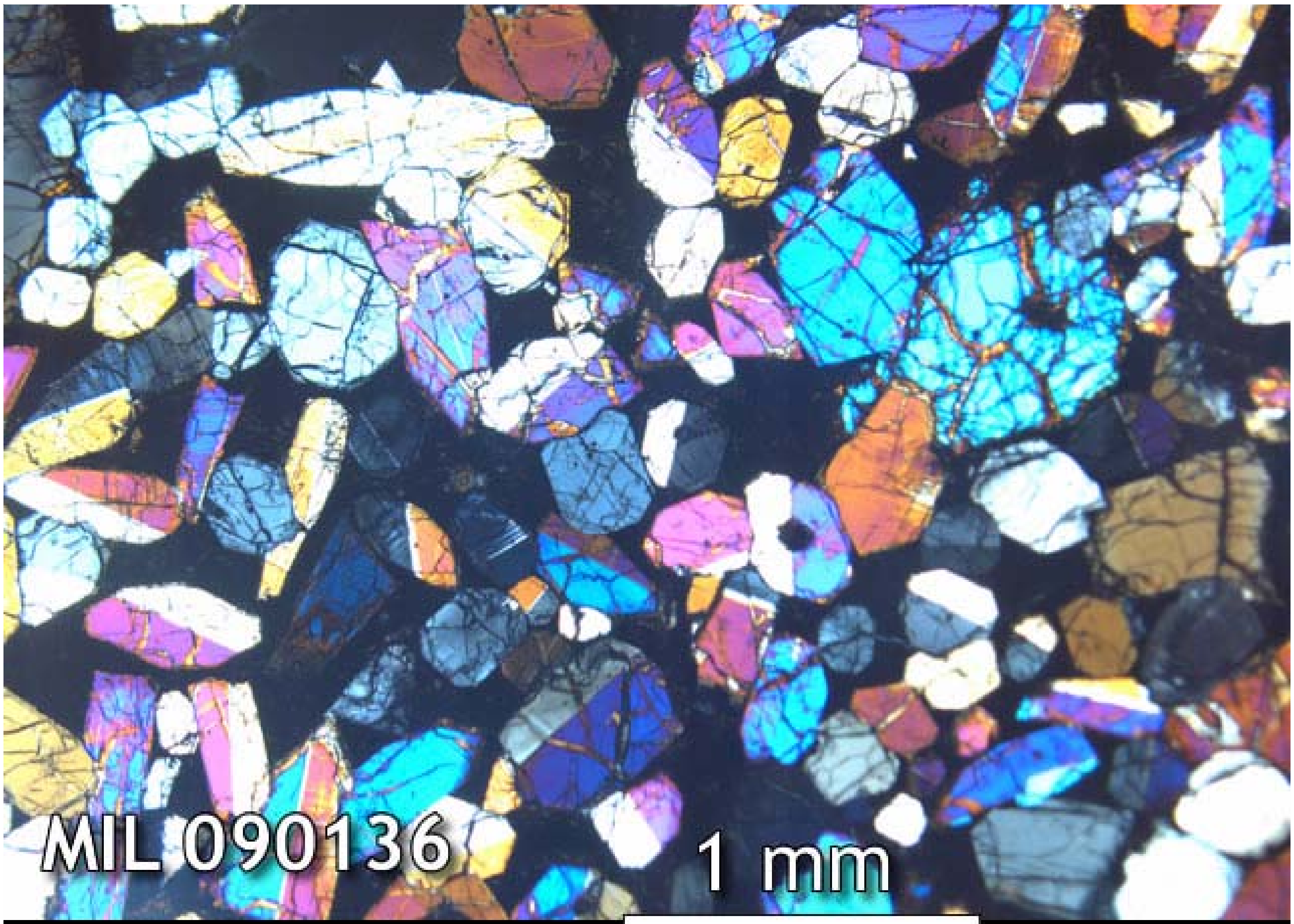
Desert) and that this might indicate the alteration is pre-terrestrial. Stopar *et al.* (2005) report that "gypsum is found in cracks, voids and veins throughout the thin sections." Sautter *et al.* (2005, 2007) report Cl-rich amphibole, chlorite, phosphaste and a "mixed sulfate of Fe and S" which they interpret as derived from a soil component on Mars. Day *et al.* (2006) find that this alteration assemblage in MIL03346 is probably a sub-micrometer mixture of smectitie clay, iron oxyhydroxides and salt minerals, with up to 14 wt. % H_2O (as OH groups).

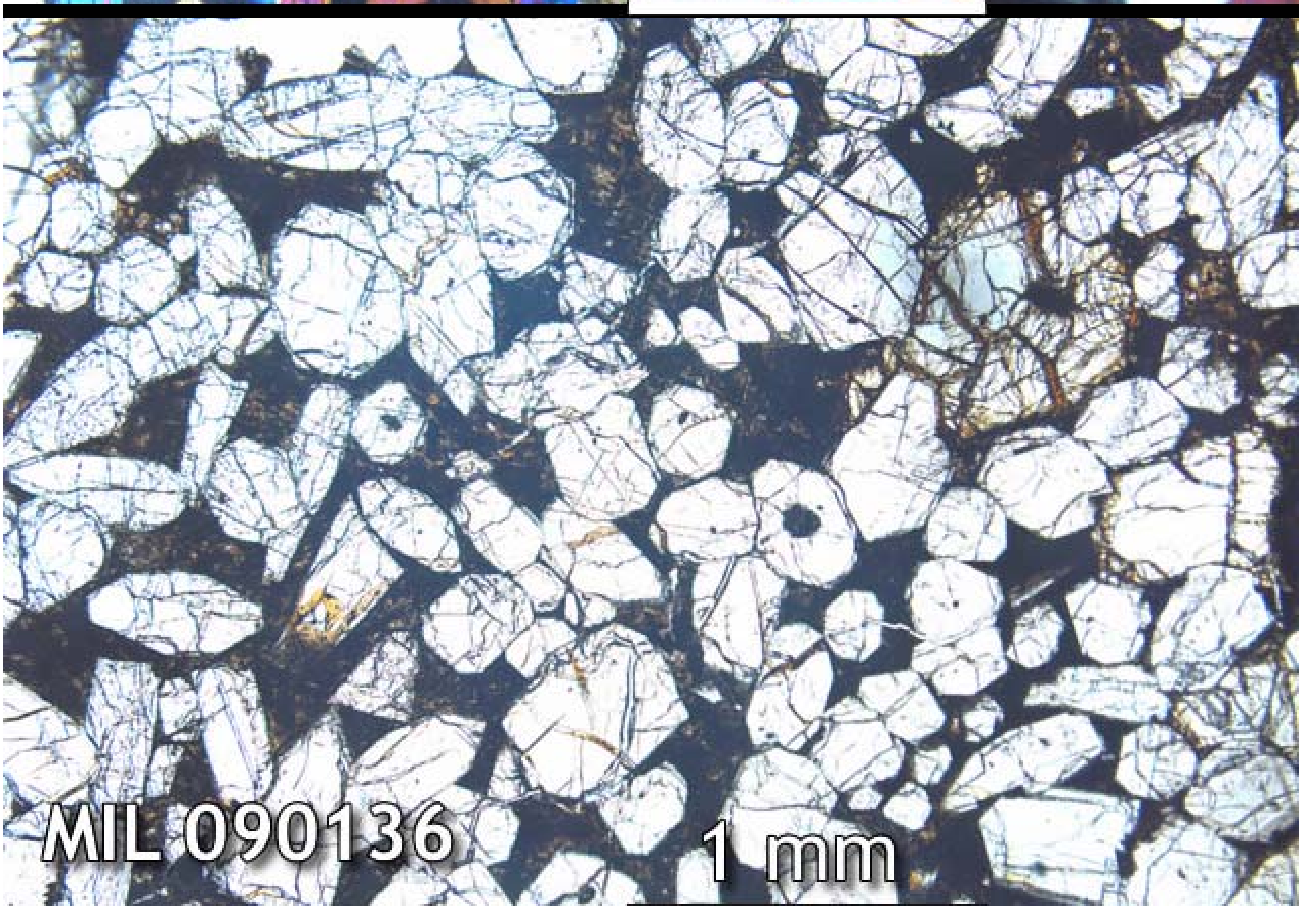
Mineral Chemistry

Olivine: MIL has less olivine (3%) than the other nakhlites (Day *et al.* 2006). McKay and Schwandt (2005) found that large olivine grains (up to 1.7 mm) have uniform cores Fo_{44-43}, but zone to Fo_5 at their outer

Mineralogical Mode for MIL 03346

	Stopar et al. 2005	Rutherford et al. 2005	McKay and Schwandt 05	Anand et al. 2005	Mikouchi et al. 05	Day et al. 06	Imae and Ikeda07
Olivine	2 vol. %	tr.	4.6		4	1.1	0.8
Pyroxene	78	65	79.8	75	74	78.4	67.7
Plagioclase						0.1	
Mesostasis	19	35	15.7	25	22	19.8	31.5
Opaques			0.9			1	
"alteration"	0.9					0.24	


MIL 090136
1 mm


MIL 090136
1 mm

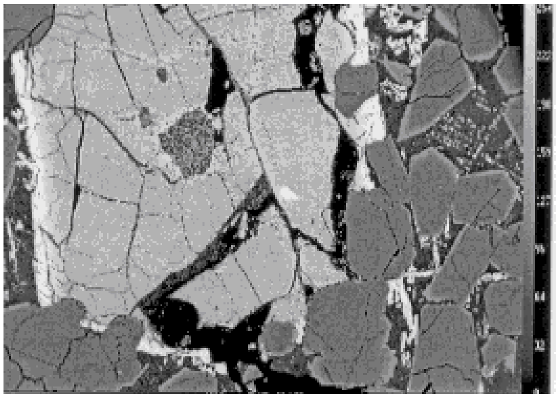


Figure 4: BSE image of large olivine (500 microns) with Fe-rich rim (from Rutherford et al. 2005).

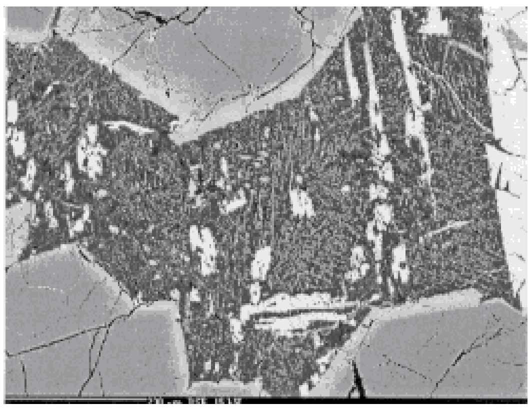


Figure 5: BSE image of matrix of MIL 03346 showing skelytal magnetite and also Fe-rich rim on euhedral clinopyroxene (Rutherford et al. 2005).

rims (figure 4). Tiny skeletal fayalite is found in the mesostasis.

Pyroxenes: Cores of clinopyroxene cluster around $Wo_{39}En_{27}$. The rims zone increase in Fe and decrease in Ca to ~$Wo_{34}En_{14}$. Mikouchi *et al.* (2005), Anand *et al.* (2005) and McKay and Schwandt (2005) found that the outer rims, adjacent to the mesostasis, zone to ferro-heddenbergite (figure 6). Imae and Ikeda found that the outer rims of pyroxene phenocrysts contain up to 10 wt.% Al_2O_3. Domeneghetti *et al.* (2006) found the iron in MIL was oxidized (Fe^{+3}).

Ti-magnetite: Dendritic chains of Ti-magnetite are prevalent in the mesostasis (similar to NWA 817). Day *et al*. (2006) determined that magnetite was chemically zoned from pure magnetite towards ulvospinel (figure 7). Both Dyar *et al.* (2006) and Morris *et al.* (2006) reported magnetite in their Mossbauer spectra.

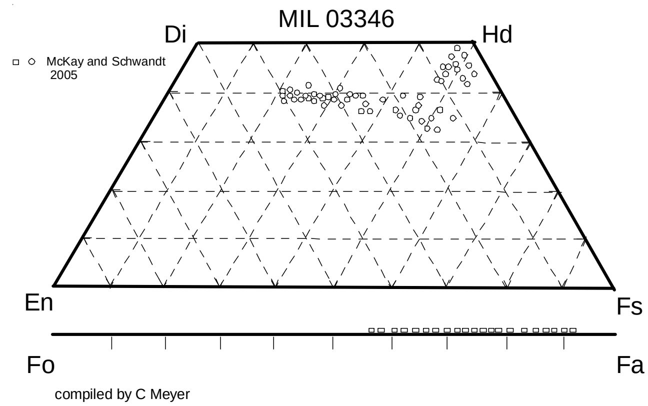


Figure 6: Pyroxene and olivine compositions of MIL 03346 (from McKay and Schwandt 2005).

Glass: Feldspathic-glass compositions in the mesostasis are $An_{29-38}Or_{7-14}$ (Anand *et al.* 2005; Day *et al.* 2006).

Silica: Anand *et al.* (2005) and Mikouchi *et al*. (2005) report small (5 micron) blebs of silica in the mesostasis. Chennaoui Aoudjehane *et al*. (2006) used cathodoluminescence to study shock effects.

Amphibole: Sautter *et al*. (2006, 2007) reported the presence of Cl-rich amphibole (1.5 to 7% Cl) in melt inclusions in augite and in olivine.

Phosphates: Fries *et al*. (2006) studied phosphates in MIL03346 by confocal Raman imaging techniques and found that they were "hydrated".

Sulfides: Day *et al.* (2006) find that sulfide "blebs" are pyrrhotite – often altered.

Jarosite: The Martian sulfate mineral jarosite has been discovered in melt inclusions in augite (McCubbin *et al*. 2008) and in the intersticies of MIL03346 (Vicenzi *et al.* 2007).

Saponite ? Imae and Ikeda (2007) repoted an occurance of a hydrated phase (saponite?), adjacent to fayalite, in a trapped melt inclusion – suggesting that the alteration occurred on Mars.

Whole-rock Composition

The whole rock composition has been determined by Anand *et al*. (2005), Barret *et al.* (2006) and Day *et al.* (2006) (table 1). Barret et al. found that Co, Ni, Cu and Zn were similar to other nakhlites. The large ion

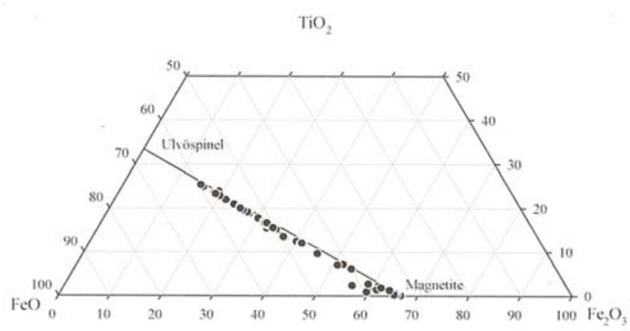


Figure 7: Composition of magnetite-ulvospinel in MIL (Day et al. 2006).

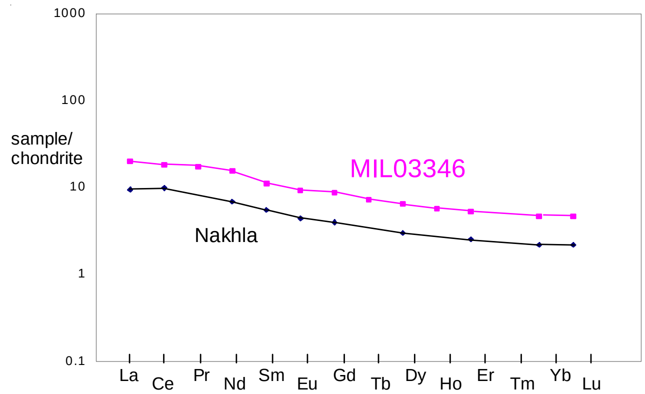


Figure 8: *Normalized rare-earth-element pattern for MIL03346 compared with that of Nakhla. Data from Barrat et al. 2006 and Nakamura et al. 1973.*

lihophile elements are similar to, but elevated, compared with Nakhla (figure 8). Note the lack of any Eu anomaly. Dreibus *et al.* (2006) reported 147 ppm F, 248 ppm Cl, 0,45 ppm Br, 610 ppm S and 315 ppm carbon. Shirai and Ebihara (2008) have also analyzed MIL03346 (data reported in diagrams).

Radiogenic Isotopes

Murty *et al.* (2005) determined a U,Th-^{4}He age of 1.02 ± 0.15 b.y. and K-Ar age of 1.75 ± 0.26 b.y. (based on U, Th, K contents of Nakhla!). Bogard and Garrison (2006) determined an Ar plateau age of 1.44 ± 0.02 b.y. (figure 9). Shih *et al.* (2006) determined a Rb-Sr isochron of 1.29 ± 0.12 b.y. and a Sm-Nd isochron of 1.36 ± 0.03 b.y. (figures 10 and 11).

Cosmogenic Isotopes

Murty *et al.* (2005) determined an average exposure age of 9.5 ± 1.0 m.y. for MIL 03346, which is the number one gets for all the nakhlites.

Other Studies

For some reason or other, the all important oxygen isotopes have not been reported, although the isotopes of S and Cl have (Kim and Farquhar 2008; Nakamura et al. 2011).

Wadhwa and Borg (2006) found that the ^{142} Nd and ^{182} W isotopic anomolies were similar to other nakhlites, concluding that nakhlites formed under relatively oxidizing conditions.

Murty *et al.* (2005) reported the isotopic ratios of rare gases extracted at different temperatures from MIL 03346.

Dyar *et al.* (2005) determined the Mossbauer, reflectance and thermal emission spectra of MIL03346 (figures 12, 13 and 14), claiming that this rock is highly oxidized with abundant Fe^{3+}. Roechette *et al.* (2005) reported the magnetization.

Processing

During initial processing, a 1 cm thick slab was cut through the center of MIL 03346 (figure 15) (McBride *et al.* 2005). About 45 thin sections were initially prepared and allocated (see diagram).

MIL 03346 was examined and split in dry-nitrogen glove boxes at JSC which have been thoroughly cleaned and dried immediately before processing of this sample. The sample was only exposed to stainless steel, aluminum and Teflon, although the gloves, gaskets and band saw wheels are made of Neoprene and/or Viton. However, the sample itself was only handled with Teflon overgloves.

Righter and McBride (2011) have summarized the processing and allocation of this rock (57 thin section, 63 chips, as of last year).

References for MIL nakhlites

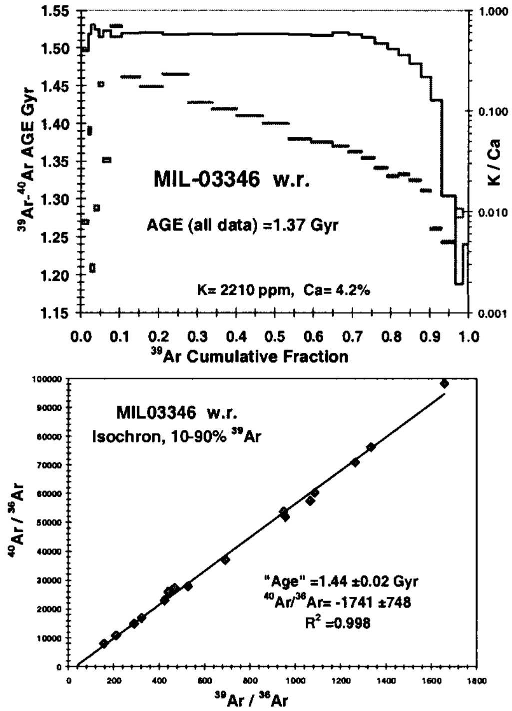


Figure 9: *Ar/Ar age dating of MIL03346 by Bogard and Garrison 2006.*

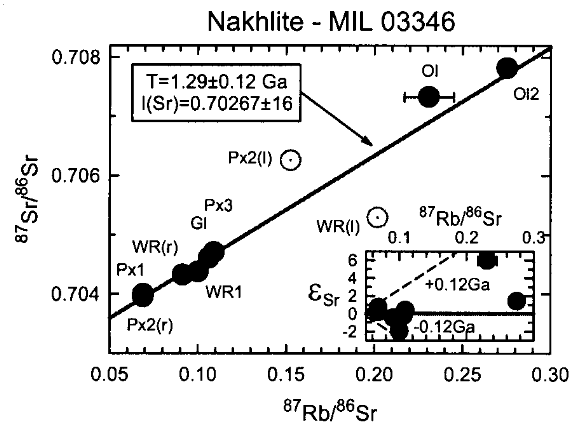


Figure 10: *Rb-Sr isochron diagram for MIL03346 by Shih et al. 2006.*

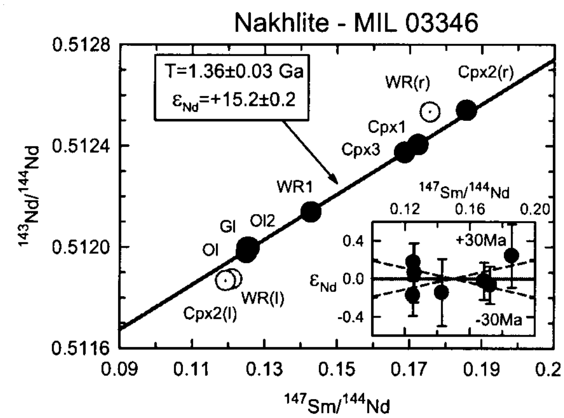


Figure 11: *Sm-Nd isochron diagram for MIL03346 by Shih et al. 2006.*

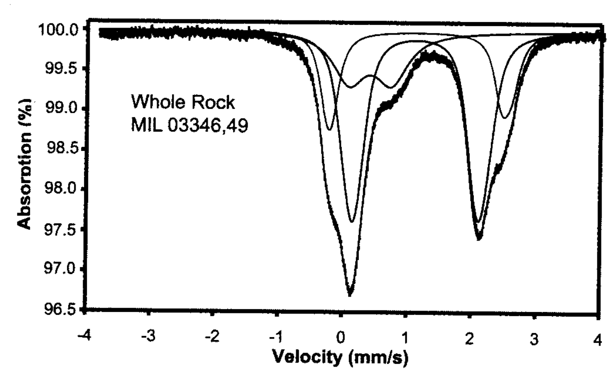


Figure 12: *Mossbauer spectra of MIL03346 from Dyar et al. 2006.*

Age data for MIL03346

	Ar/Ar	Rb/Sr	Nd/Sm
Bogard and Garrison 2006	1.44 ± 0.02 b.y.		
Shih et al. 2006		1.29 ± 0.12	
			1.36 ± 0.03

Table 1. Chemical composition of MIL 03346.

reference	Anand2005	Barret2006		Day2006	
weight					
SiO2 %	49.2			49.5	(b)
TiO2	0.07	0.69	(a)	0.68	(b)
Al2O3	3.59	3.66	(a)	4.09	(b)
FeO	19.23	19.12	(a)	19.1	(b)
MnO	0.45	0.46	(a)	0.46	(b)
MgO	9.33	9.99	(a)	9.26	(b)
CaO	15	15.75	(a)	14.4	(b)
Na2O	1.01	1	(a)	0.96	(b)
K2O	0.29	0.27	(a)	0.2	(b)
P2O5	0.22	0.25	(a)	0.23	(b)
S %				0.06	(b)
sum					
Sc ppm	46	54.5	(a)	52.9	(c)
V	184	208	(a)	210	(c)
Cr	1300	1192	(a)	1300	(c)
Co	25	35.7	(a)	38.7	(c)
Ni	60	49	(a)	58.1	(c)
Cu	13	8.2	(a)	13.3	(c)
Zn	65	61.3	(a)	61.5	(c)
Ga		6.51	(a)	6.77	(c)
Ge ppb					
As					
Se					
Rb		4.14	(a)	4.41	(c)
Sr	106	131.7	(a)	121.3	(c)
Y	7	8.44	(a)	8.5	(c)
Zr		23.29	(a)	21.2	(c)
Nb		3.98	(a)	3.65	(c)
Mo					
Ru					
Rh					
Pd ppb					
Ag ppb					
Cd ppb					
In ppb					
Sn ppb					
Sb ppb					
Te ppb					
Cs ppm		0.29	(a)	0.27	(c)
Ba	53	59.58	(a)	56.9	(c)
La		4.7	(a)	3.89	(c)
Ce		11.01	(a)	11.3	(c)
Pr		1.56	(a)	1.78	(c)
Nd		7.07	(a)	8.04	(c)
Sm		1.64	(a)	1.83	(c)
Eu		0.522	(a)	0.52	(c)
Gd		1.73	(a)	1.86	(c)
Tb		0.266	(a)	0.3	(c)
Dy		1.57	(a)	1.66	(c)
Ho		0.317	(a)	0.32	(c)
Er		0.851	(a)	0.84	(c)
Tm				0.13	(c)
Yb		0.766	(a)	0.8	(c)
Lu		0.114	(a)	0.13	(c)
Hf		0.69	(a)	0.66	(c)
Ta		0.23	(a)	0.21	(c)
W ppb		0.4	(a)		
Re ppb					
Os ppb					
Ir ppb					
Pt ppb					
Au ppb					
Th ppm		0.42	(a)	0.43	(c)
U ppm		0.09	(a)	0.11	(c)

technique: (a) ICP, (b) e.probe (c) ICP-MS

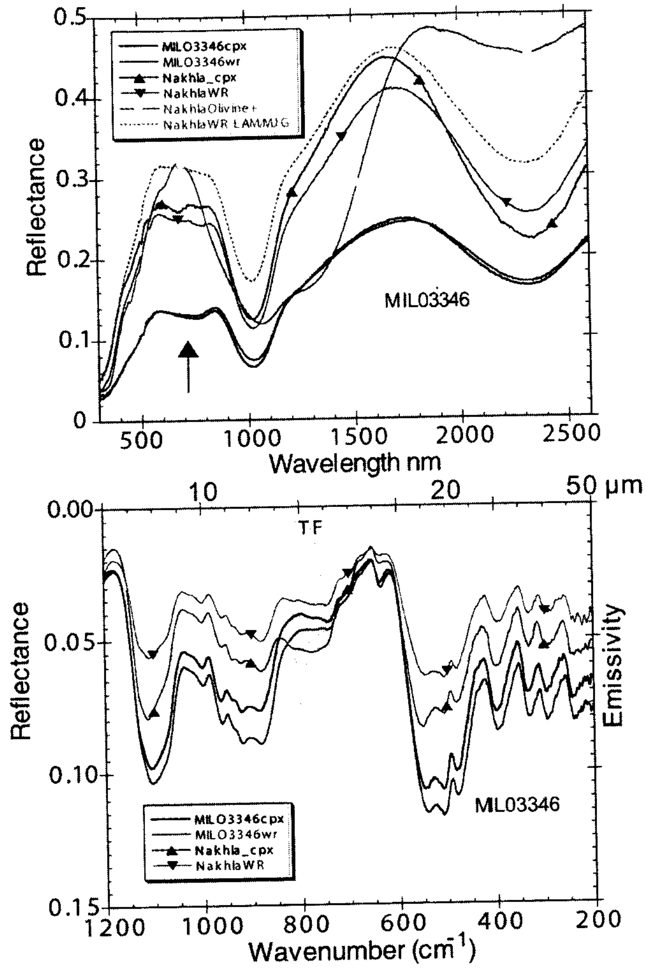


Figure 13: *IR-visible-UV reflectance specta for MIL03346 (dominated by clinopyroxene) from Dyar et al. 2006.*

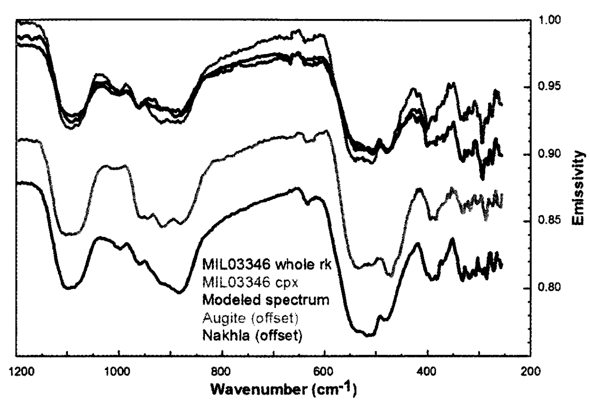


Figure 14: *Thermal emission spectra of MIL03346, Augite and Nakhla from Dyar et al. 2006.*

Figure 15: *Sawn surfaces of MIL03346,66 and slab ,61. Sacle is in cm. (photo courtesy of Kathleen McBride).*