Miller Range 05035

Unbrecciated basalt

142 g

Figure 1: MIL 05035 as found in the ice in the Miller Range.

Introduction

Miller Range 05035 (Fig. 1) was found during the 2005-2006 ANSMET field season (Fig. 2), and was announced in the August 2006 Antarctic Meteorite Newsletter (Figs. 3 and 4). The exterior has about 95% black, shiny fusion crust. The interior is pinkish-tan in color with no rusting. The rock is moderately hard and has an unusual granular texture with a vague resemblance to granite. There are numerous inclusions; linear white features a few mm in length, melted appearing black, glassy inclusions with an iridescent "peacock ore" opalescent sheen, a transparent, glass like mineral, and a few clay-like powdery areas.

Mineralogy and Petrography

The section exhibits an unbrecciated texture of coarse-grained (several mm) pyroxene and maskelynite (Fig. 5, 6) with interstitial sulfides, iron-titanium oxides, intergrowths of fayalite-silicate-augite (Fig. 6, 7a), and other late-stage glasses (Fig. 7b) and minerals (incl. BaO-enriched potassium feldspar). Pigeonite and augites contain fine exsolution lamellae (Fig. 6, 7c), and are overall are strongly zoned with a range of compositions (Fig. 8). The zoning is very reproducible from section to section, and along with minor elements defines a fractionation trend (Fig. 8, 9). Plagioclase (maskelynite) is $An_{83-92}Or_{0-2}$ (Joy et al., 2007, 2008; Liu et al., 2007, 2009; Arai et al., 2007, 2009). Minor and trace element data for individual mineral phases is presented by Joy et al. (2008) and Liu et al. (2009) using Laser ablation and ion microprobe techniques, respectively. We have chosen not to summarize the many data reported therein, but instead alert the reader to these rich datasets.

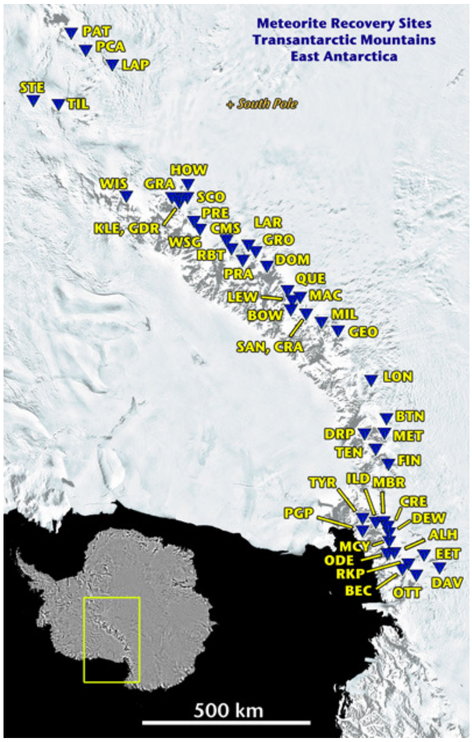

Figure 2: The Miller Range region of Antarctica (where MIL 05035 was found), is near the center of the map at the edge of the Trans Antarctic Mountains.

Figure 3: Photos of MIL 05035 taken in the Antarctic Meteorite Processing Lab at NASA-JSC.

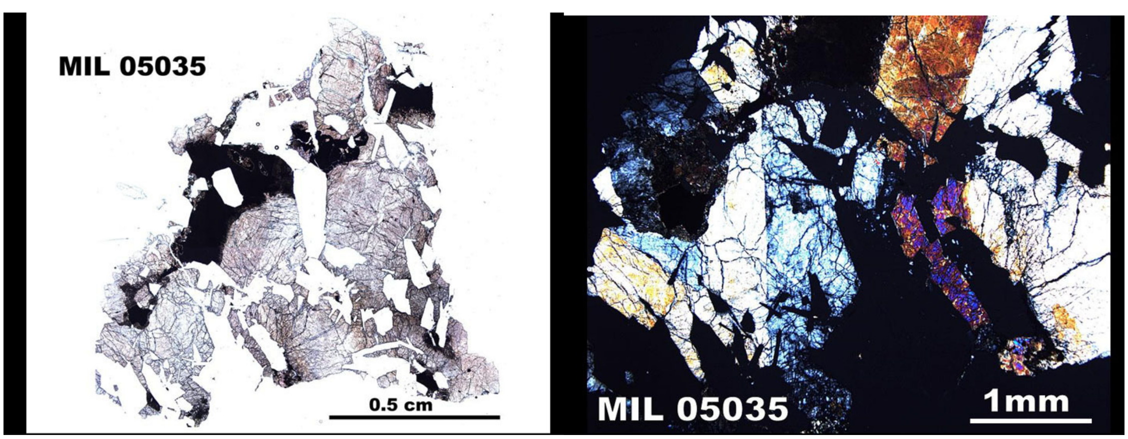

Figure 4a: Low magnification plane polarized light images of section MIL05035 ,4.; Figure 4b: Higher magnification crossed nicols image of a different region of MIL05035 ,4.

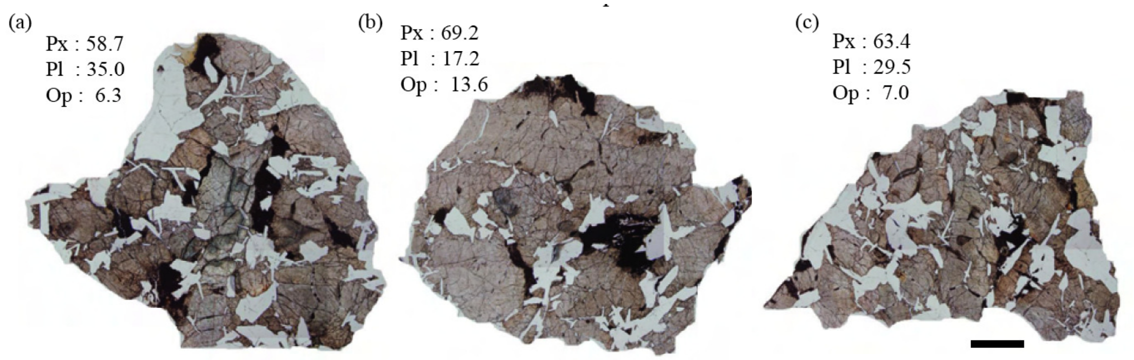

Figure 5: three different sections and subsamples of MIL 05035, illustrating the variation in modal mineralogy given the coarse-grained nature of the sample (from Arai et al., 2007, 2009).

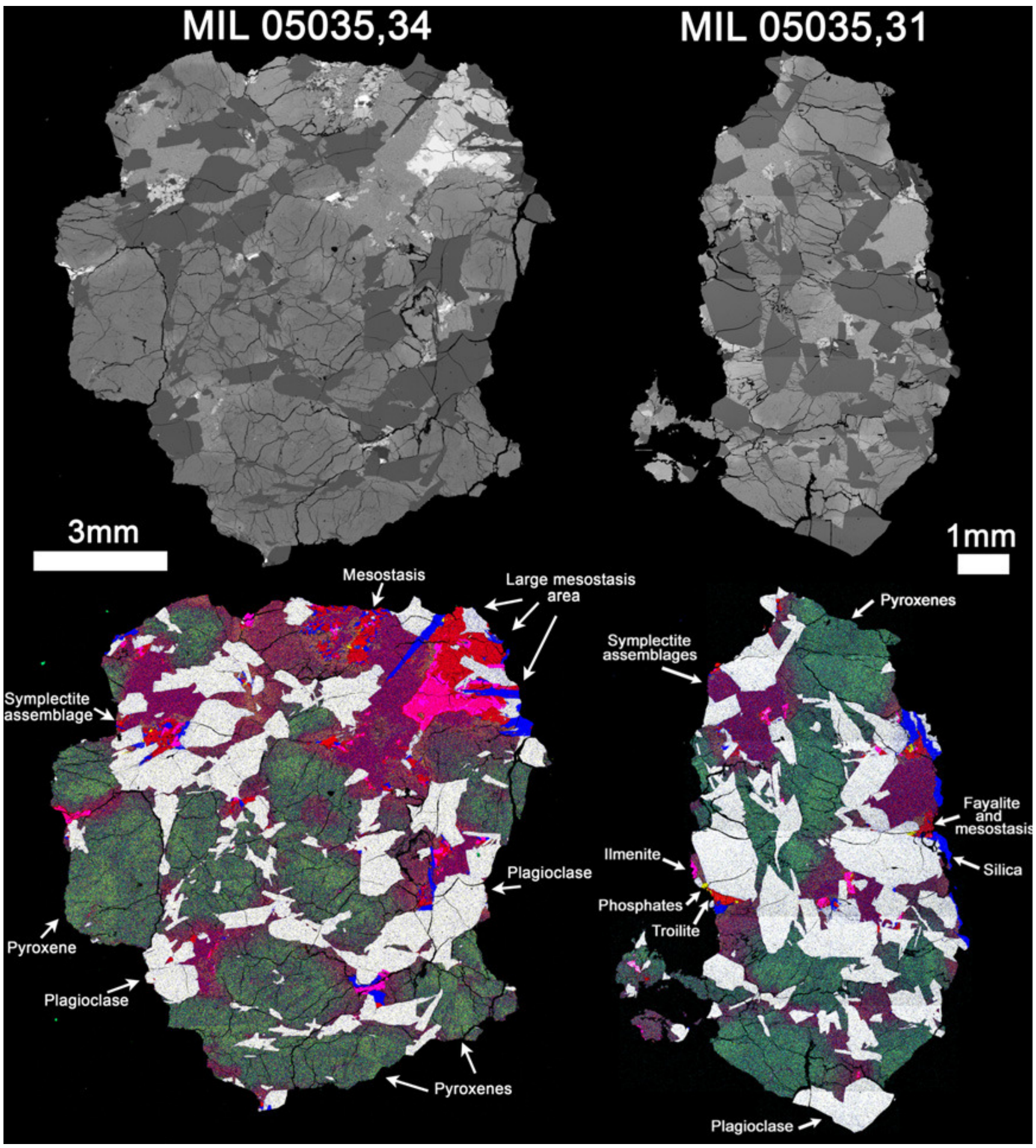

Figure 6: X-ray map of split of MIL 05035 (,34 and ,31) showing major phases of pyroxene (green), maskelynitized plagioclase (white) and symplectites (dark purple), as well as minor silica (blue), troilite (red), phosphates (yellow) and ilmenite (light purple) (from Joy et al., 2008).

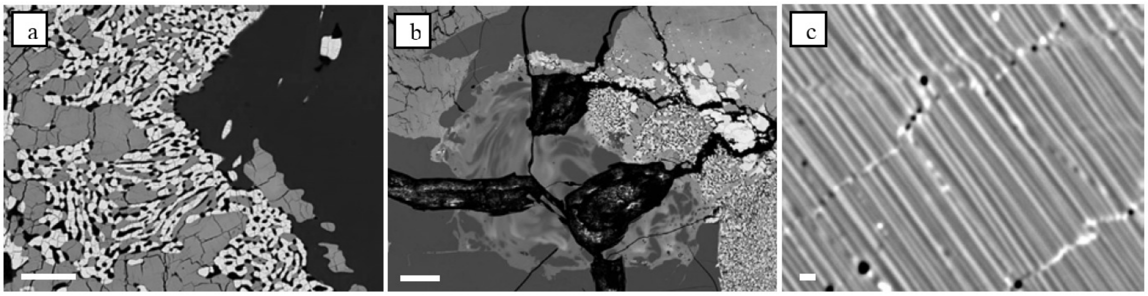

Figure 7: BSE images of three different textures in MIL 05035: a) symplectitic texture at grain boundary between pyroxene and maskelynite – phases are hedenbergite, ferrosilite and SiO_2 (30 μm scale bar), b) heterogeneous shock melt glass (100 μm scale bar), and c) fine grained exsolution lamellae in pyroxene (1 μm scale bar) (from Arai et al., 2007, 2009).

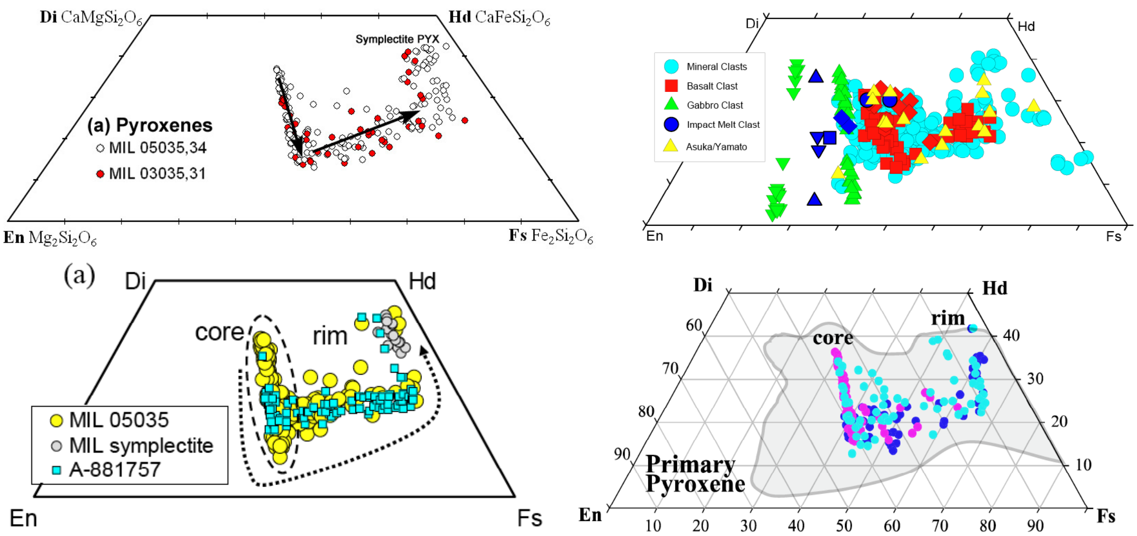

Figure 8: Pyroxene compositions from MIL 05035 taken from four different studies illustrating the same trend of compositional variation from augite to ferroaugite. From the studies of (clockwise from upper left) Joy et al. (2007, 2008), Zeigler et al. (2007), Arai et al. (2007, 2009) and Liu et al. (2007, 2009).

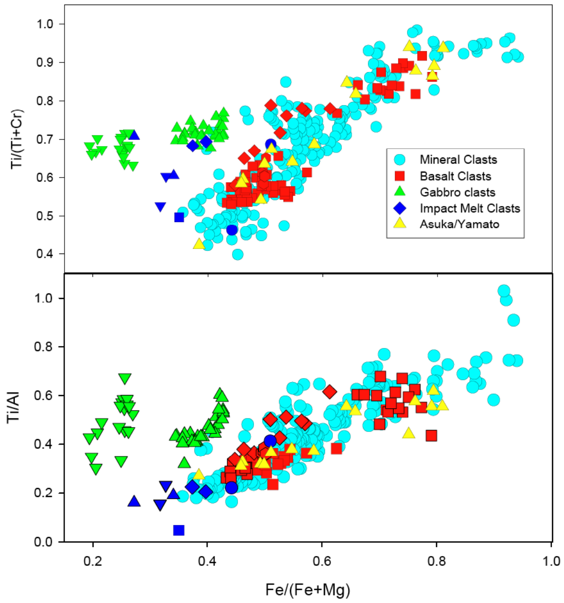

Figure 9: Pyroxene minor element variation – Ti, Al and Cr – measured in MIL 05035 pyroxenes (from Zeigler et al., 2007).

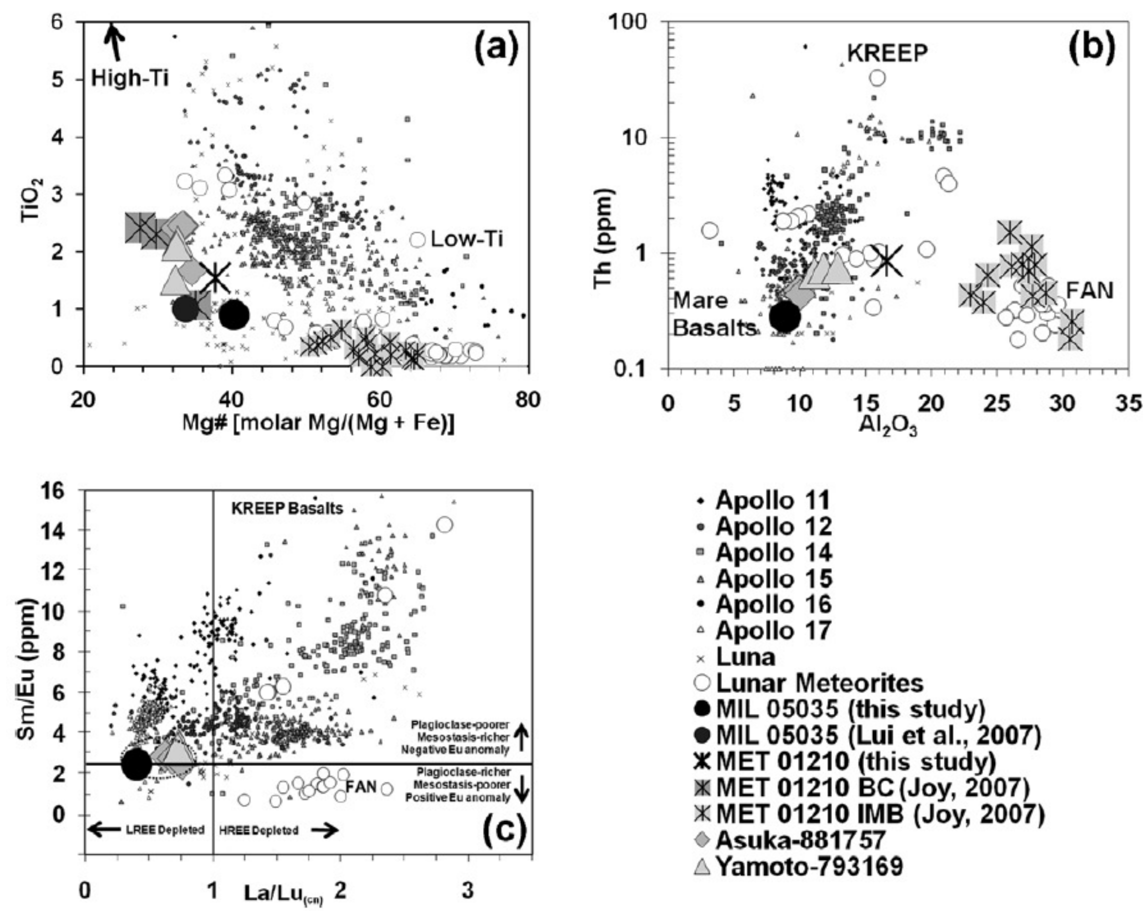

Figure 10: Whole rock composition of MIL 05035 demonstrates it distinct composition relative to other mare basalts with low TiO2 contents (~1 wt%), low Al_2O_3 (~8 wt%), and LREE depletion compared to other Apollo and lunar basaltic meteorite samples (from Joy et al., 2008). In fact, there is some similarity to the composition of Luna 24 basalts.

Chemistry

Compositionally, MIL 05035 is somewhat typical of low Ti basalt, containing high FeO (near 21 wt%), low Al_2O_3 (~ 8 wt%), and low Th (0.3 ppm). It has low light REE compared to many other lunar basalts (Fig. 10), and based on composition, texture, age and mineralogy, some have argued that MIL 05035 is launch paired with Asuka 881757 and Yamato 793169 (Zeigler et al., 2007; Arai et al., 2007, 2009; Liu et al., 2009). The LREE depletion and low Ti nature has led many to suggest it originated from a location distant from the Procellarum KREEP Terrane (Liu et al., 2009; Arai et al., 2009; Joy et al., 2008), on either the nearside or the farside.

Radiogenic age dating

Ar-Ar dating has ages of 3.910 and 3.845 Ga for two different aliquots (Fig. 11; Fernandes et al., 2009). Initial studies of the Sr and Nd isotopic systems have also shown that MIL 05035 is an old low Ti basalt, similar in age to the Asuka 881757 gabbro, yielding ages between 3.8 and 3.9 Ga (Figs. 12-13). In fact, the low Rb/Sr of MIL 05035 is in the same range as that for the Yamato 793169, Asuka 881757 basaltic lunar meteorites, suggested to have a unique olivine and pyroxene rich source region distinct from many Apollo basalts (Misawa et al., 1991; Kita-Torigaye et al., 1993). The combination of mineralogical, petrologic, geochemical, chronologic, and temporal similarities between Yamato 793169, Asuka 881757, MIL 05035, and MET 01210 have led many to suggest that these samples are launch paired (Arai et al., 2009; Joy et al., 2008; Liu et al., 2009). Arai et al (2009) offer a carton that relates these four samples petrologically (Fig. 14).

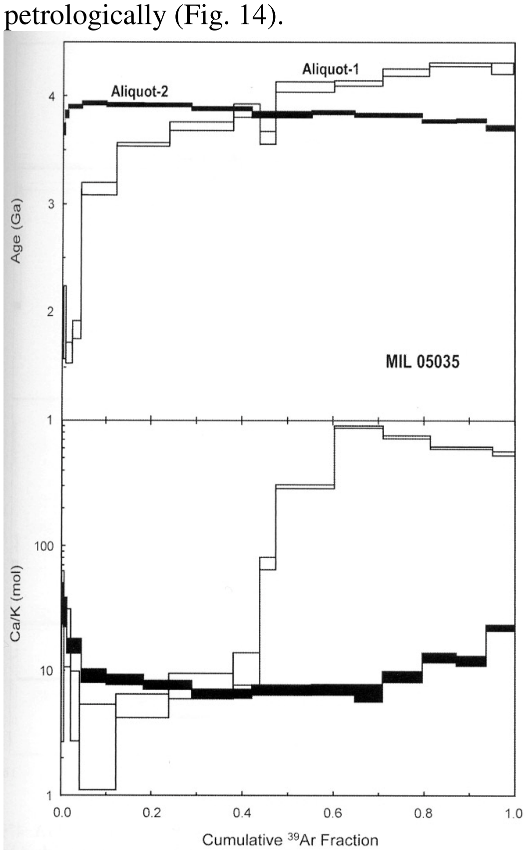

Figure 11: Ar-Ar plateau age for two aliquots of MIL 05035 (from Fernandes et al., 2009).

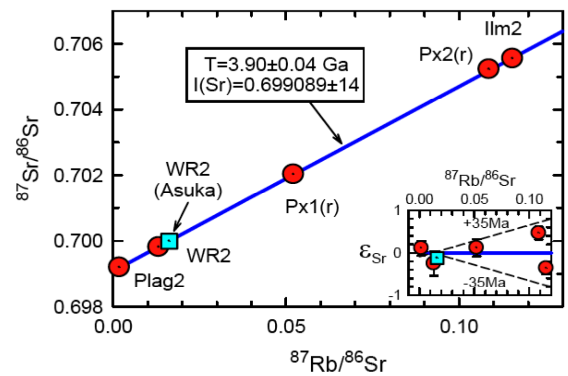

Figure 12: Rb-Sr mineral and whole rock isochron yielding an age of 3.90 Ga for MIL 05035 (Nyquist et al., 2007).

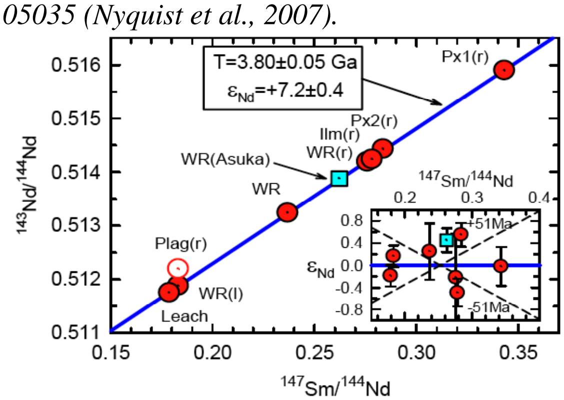

Figure 13: Sm-Nd mineral and whole rock isochron yielding an age of 3.80 Ga for MIL 05035 (Nyquist et al., 2007).

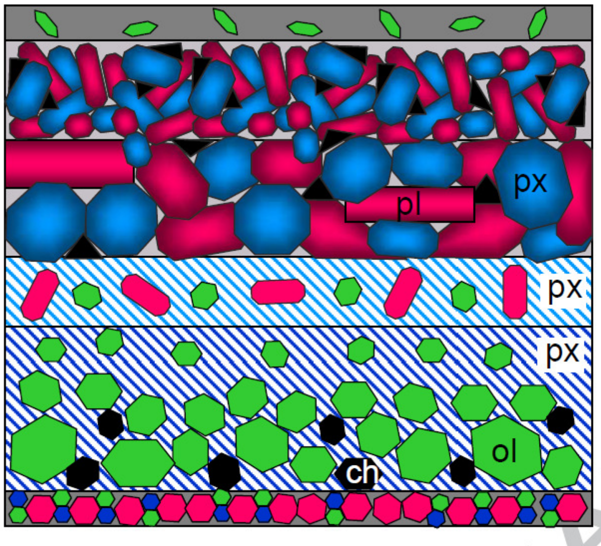

Figure 14: Cartoon illustrating the possible petrologic link between the YAMM (Yamato 793169, Asuka 881757, MIL 05035, and MET 01210) lunar meteorites (from Arai et al., 2009).

Processing

MIL 05035 has been extensively studied and allocated to approximately 15 different scientists (Table 2), leaving the main mass close to 90 g.

Table 1a. Chemical composition of MIL 05035

reference	1,2	3,4
weight (mg)	20	140
Technique	b	a,b
SiO_2 %	47	48.4
TiO_2	1.44	0.9
Al_2O_3	9.26	8.85
FeO	22	20.7
MnO	0.32	0.33
MgO	7.44	7.79
CaO	11.8	12.1
Na_2O	0.26	0.21
K_2O	0.03	0.01
P_2O_5	0.05	0.02
S %	0.055	
Sum	100	99.6
Sc ppm	93.7	109
V	105	107
Cr	2258	2052
Co	23.8	28.1

Ni	8.27	11
Cu	5.21	9.64
Zn	1.81	16.9
Ga	3.07	2.96
Ge	1	0.12
As		
Se		
Rb	0.57	0.49
Sr	113	105
Y	19.7	22.1
Zr	32.3	36.4
Nb	1.94	1.15
Mo		
Ru		
Rh		
Pd ppb		
Ag ppb		
Cd ppb		
In ppb		
Sn ppb		
Sb ppb		
Te ppb		
Cs ppm	0.02	0.03
Ba	28.4	25.8
La	1.87	1.54
Ce	5.28	4.58
Pr	0.81	0.75
Nd	4.59	4.24
Sm	1.87	1.77
Eu	0.82	0.72
Gd	2.54	2.65
Tb	0.52	0.56
Dy	3.66	3.93
Ho	0.82	0.88
Er	2.33	2.66
Tm	0.36	0.39
Yb	2.83	2.78
Lu	0.4	0.39
Hf	1.21	1.03
Ta	0.1	0.06
W ppb	310	10
Re ppb		
Os ppb		
Ir ppb		
Pt ppb		
Au ppb		
Th ppm		0.28
U ppm		0.07

technique (a) ICP-AES, (b) ICP-MS, (c) IDMS, (d) Ar

Table 1b. Light and/or volatile elements for MIL 05035

Li ppm	8.45	9.63
Be		
C		
S		
F ppm		
Cl		
Br		
I		
Pb ppm	0.42	0.39
Hg ppb		
Tl		
Bi		

References: 1) Liu et al. (2007); 2) Liu et al., 2009); 3) Joy et al. (2007); 4) Joy et al. (2008).

Table 2: Split allocations of MIL 05035 (1/10)

Split	Parent	Mass (g)	PI or Location	comment
0	0	90.985	JSC	Doc Pc
5	1	0.01	McCoy SI	Thin section
6	1	0.01	L.A. Taylor	Thin section
9	2	0.801	Nishiizumi	Int chip
11	2	2.032	Nyquist	Int chip
12	2	0.297	Nishiizumi	Loc Int chip
13	2	0.255	Fernandes	Int chip
14	2	0.45	Korotev	Int chip
16	2	0.555	Mikouchi	Int chip
17	2	0.334	Arai	Int chip
19	2	0.361	S. Russell	Int chip
20	2	1.938	L.A. Taylor	Sm Int chips
28	18	0.01	Mikouchi	Thin section
29	18	0.01	Arai	Thin section
30	18	0.01	Anand	Thin section
31	18	0.01	Hsu	thick section
32	23	0.01	Mikouchi	Thin section
33	23	0.01	Arai	Thin section
34	23	0.01	Lee	thick section
35	15	0.01	Korotev	Thin section
36	1	0.01	Arai	Thin section
37	1	0.01	Anand	Thin section
38	1	0.01	Cohen	Thin section
40	15	0.01	L.A. Taylor	thick section
41	15	0.01	Boesenberg	Thin section
42	23	0.01	Boesenberg	Thin section
43	23	0.331	Pieters	Int chips
45	23	0.01	JSC	Thin section
46	25	0.218	Jull	Int chip