PETROGRAPHY AND BULK COMPOSITION OF MILLER RANGE 05035: A NEW LUNAR VLT GABBRO.

K. H. Joy[1,2,3], M. Anand[2,4], I. A. Crawford[1], and S. S. Russell[2]. k.joy@ucl.ac.uk [1] UCL/Birkbeck Research School of Earth Sciences, UCL, Gower Street, London, WC1E 6BT, UK. [2]The Natural History Museum, Cromwell Road, London SW7 5BD, UK. [3]RAL, CCLRC, Didcot, Oxon, OX11 0QX, UK. [4] Department of Earth Sciences, CEPSAR, The Open University, Milton Keynes, MK7 6AA,UK.

Introduction: Miller Range (MIL) 05035 is a crystalline lunar mare gabbroic meteorite collected in Antarctica in 2005 [1]. It is an important new sample in the lunar meteorite (LM) collection as it is only one of ~8 to be classified as basaltic in nature. MIL 05035 is coarsely grained with large pyroxene grains (≤8mm) subophitically enclosing plagioclase grains (≤6mm), and accessory ilmenite, spinel, silica and sulphide phases.

Methods: Minerals in MIL 05035,31 and MIL 05035,34 were investigated using a Cameca SX50 Wavelength Dispersive electron microprobe. Mineral X-ray maps were made using a LEO 1455VP SEM fitted with Oxford Instruments INCA energy dispersive X-ray spectrometer and bulk major- and trace-element chemistry was obtained using ICP-AES and ICP-MS techniques on 140 mg chip of MIL 05035,19 (Table 1).

Lunar Origin: Fe to Mn ratios in the bulk rock (62), and in pyroxene (average: 60) and olivine phases (average: 80), bulk rock Co/Cr (0.014), and a typical lunar anhydrous mineralogy confirm lunar origin for this meteorite. We will report the results on ongoing oxygen isotope analysis at the LPSC 2007 meeting.

Petrography: MIL 05035 is an unbrecciated, holocrystalline lunar gabbroic meteorite. Its coarse-grained nature suggests a slow cooling history in a thick lava flow.

Pyroxenes: are the dominant mineral phases in MIL 05035 (~54% of sample ,31 by mode). They are typically large with compositional zoning from calcic-augite and pigeonite cores to Fe-rich calcic-augite rims: Fs_{29-68},Wo_{13-43},En_{2-42} (Fig.1a,2).

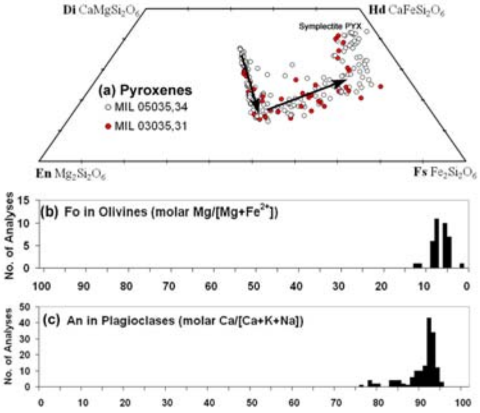

Fig. 1. Mineral compositional variation in MIL 05035 (a) pyroxene variations where the melt evolution is tracked with the black arrow, (b) olivine, and (c) plagioclase compositional variations.

Extreme fractionation is evident in terms of Fe-rich rims associated with late stage crystallization products. Ferrosilite breakdown symplectitc assemblages (silica + fayalitic olivine + hedenbergitic pyroxene) occur at the rims of many pyroxene grains in a similar texture observed in LM Asuka-881757 [2,3,4,5,6]. These aggregates in places cover broad areas of MIL 05035 (~6% by mode: Fig.2), and suggest that the sample may have crystallized at low-pressure [4].

Plagioclases: are generally large (500µm – 6mm: Fig. 2) sub-rounded grains (36% by mode) with a typical mare basaltic compositional range: $An_{76-95,}Or_{0-5}$ (Fig.1c). The vast majority of grains appear to have been completely shock metamorphosed to maskelynite.

Olivine: grains are fayalitic in composition (Fig.1b: Fo_1–Fo_{11}) and form anhedral aggregates of varying sizes (<500µm – 2µm) as part of the late-stage mineral assemblage (<1% by mode: Fig.2).

Ilmenite: is rare in MIL 05035 (<1%) and found in association with pyroxene-rim compositions and

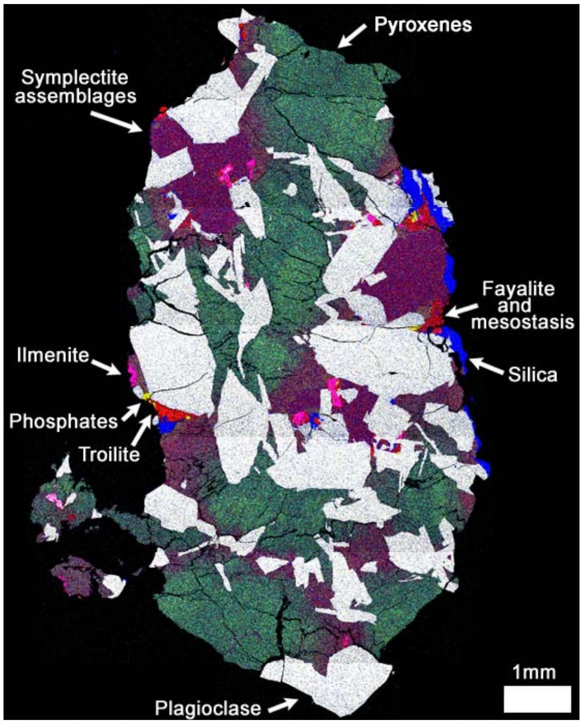

Fig. 2. False-colour X-ray map of section MIL 05035,31. Mineral phases are indicated. Colour correspond to abundance of elemental concentration and can be used to delineate mineralogical phases: White = Al (plagioclase), Red = Fe (fayalitic olivine, troilite, pyroxene rims and symplectite assemblages), Blue = Si (silica), Yellow = Ca (phosphates), Green = Mg (pyroxene cores), Pink = Ti (ilmenite and spinels)

symplectite assemblages. It occurs as euhedral elongate crystals (10µm – 500µm), and also as smaller anhedral aggregates in proximity to mesostasis areas. The very low modal abundance of ilmenite is evidence that this sample crystallized from a melt poor in TiO_2.

Sp*inels:* occur occasionally as large grains (<700 µm) that have a limited compositional range of late-stage crystallizing ulvöspinel (2^*Ti_{77-90},Al_{4-7},Cr_{4-16}). These large anhedral grains occupy an intergrowth with host ilmenite and fayalite phases. Smaller grains also occur as intergrowths in mesostasis regions.

Mesostasis: areas are found adjacent to evolved pyroxene rims and associated with the symplectite assemblage described above. Associated with these regions is fayalitic olivine, silica phases (occurring as elongate laths (<1mm) and smaller (<300µm) grains), anhedral troilite ($Fe_{61-63}S_{33-37}$) blebs, apatite, whitlockite, and occasional aggregates of small Si-rich and K-rich glass intergrowths.

Bulk composition and Lunar context: according to our measurements (Table 1) MIL 05035 can be classified as a VLT (0.9 wt. % TiO_2) low-Al (8.85 wt. % Al_2O_3), low-K (124 ppm K) mare gabbroic meteorite (Fig.3b) following the scheme proposed by [7]. It has a very high Sc-content (109 ppm) and is evolved (Mg# 40), but has low bulk ITE concentrations, and a very low Th-content (0.28ppm Th: Fig.3c) implying that it was likely crystallized distally to the Procellarum KREEP Terrane [8].

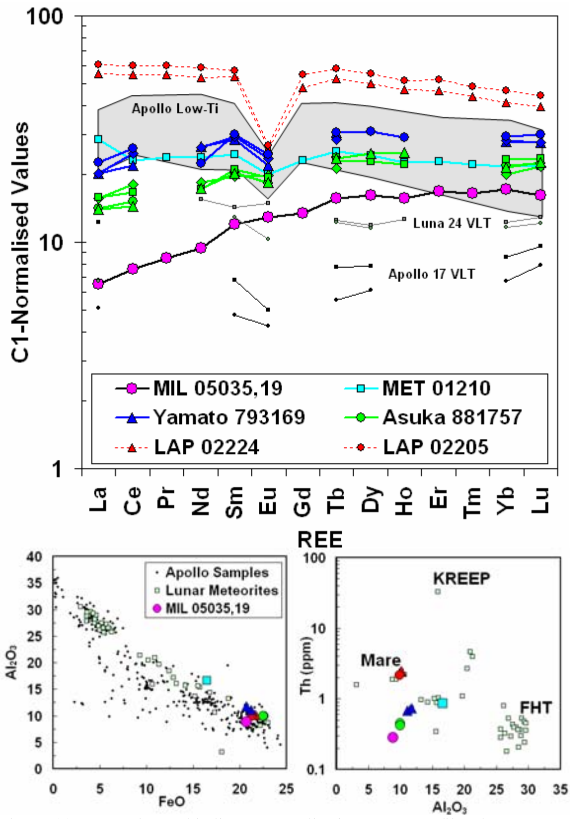

Fig. 3. (a) Comparison of bulk C1-normalised [9] REE profile of MIL 05035 compared to lunar meteorites LAP [10], MET 01210 [11], Asuka 881757 [3,5] and Yamato 793169 [3,5]. Also illustrated are the REE profiles of two Apollo 17 VLT mare basalts, two Luna 24 VLT mare basalts, and a grey field representative of Apollo Low-Ti mare basalts. (b) Comparison of MIL 05035 bulk composition to Apollo samples and the lunar meteorite collection (same colour scheme as above).

Our sample of MIL 05035 does not have a negative Eu-anomaly (Fig.3a) typical of the majority of mare basalts. It also has a low REE content, with a C1-normalised profile [9] typical of being dominated by pyroxene phases (positive LREE slope, and a relatively flat HREE profile: $(La/Lu)_n=0.4$, $(Tb/Lu)_n=1.4$). This profile is similar to that measured in the LM Yamoto-793169 and Asuka-881757 [3,5] (Fig.3a), although in comparison MIL 05035 is depleted in REE concentration and also notably lower in bulk TiO_2 content (Y and A are reported to have 1.5-2.5 wt. % TiO_2 [3,5]). MIL 05035's bulk REEs are also much lower than those in Apollo and LM low-Ti samples, but are akin to concentrations measured in A17 and Luna 24 VLT mare basalts.

Mineralogically, pyroxene and symplectite textures in MIL 05035 are similar to those reported in Asuka-881757 and to some large monomict pyroxene fragments and symplectite assemblage clasts observed in the LM regolith breccia MET 01210 [11,12].

Summary: MIL 05035 is an unusual holocrystalline, coarsely grained VLT mare gabbro sample. We propose that it is possibly paired with A-881757 and Y-793169 in terms of petrography, mineral chemistry and bulk composition.

SiO_2	48.39 ± 0.279	Li	9.63 ± 0.052	Nb*	1.15 ± 0.030	La*	1.54 ± 0.080
TiO_2	0.90 ± 0.008	Be*	0.26 ± 0.063	Mo*	0.02 ± 0.001	Ce*	4.58 ± 0.284
Al_2O_3	8.85 ± 0.070	Sc	108.98 ± 0.479	Sn*	0.41 ± 0.008	Pr*	0.75 ± 0.043
Cr_2O_3	0.30 ± 0.002	V	106.69 ± 0.579	Sb*	0.16 ± 0.015	Nd*	4.24 ± 0.243
FeO	20.68 ± 0.189	Co	28.07 ± 1.644	Cs*	0.03 ± 0.004	Sm*	1.77 ± 0.045
MnO	0.33 ± 0.003	Ni	10.98 ± 1.107	Ba*	25.76 ± 0.206	Eu*	0.72 ± 0.047
MgO	7.79 ± 0.056	Cu	9.64 ± 0.548	Hf*	1.03 ± 0.039	Gd*	2.65 ± 0.104
CaO	12.13 ± 0.112	Zn	16.91 ± 0.084	Ta*	0.06 ± 0.001	Tb*	0.56 ± 0.011
Na_2O	0.21 ± 0.002	Ga*	2.96 ± 0.087	W*	0.01 ± 0.002	Dy*	3.93 ± 0.208
K_2O	0.01 ± 0.001	Ge*	0.12 ± 0.061	Tl*	0.01 ± 0.002	Ho*	0.88 ± 0.055
P_2O_5	0.02 ± 0.001	Rb*	0.49 ± 0.009	Pb*	0.39 ± 0.013	Er*	2.66 ± 0.071
Total	**99.31**	Sr	105.20 ± 1.337	Bi*	0.02 ± 0.001	Tm*	0.39 ± 0.016
Mg #	**40.19**	Y	22.08 ± 0.120	Th*	0.28 ± 0.016	Yb*	2.78 ± 0.117
Mass	140 µg	Zr*	36.38 ± 3.961	U*	0.07 ± 0.004	Lu*	0.39 ± 0.016

Table.1. Bulk chemical composition of MIL 05035, 19 measured using ICP-AES and ICP-MS (elements denoted with a *). Elements from Li onwards are listed in ppm. Errors are reported as 2 sigma.

References: [1] Satterwhite and Righter. Antarctic Meteorite Newsletter, vol. 29(2), Sept. 2006. [2] Yanai K. et al. 1993. 24th LPSC. Part 3: 1555-1556. [3]Warren P. H. and Kallemeyn G. W. (1993) Proc. NIPR Symp. *Antarct. Meteorites* 6, 35-57. [4] Oba T. and Kobayashi Y. 2001. Antarct. Meteorite Res., Vol. 14. 21-27. [5] Koeberl C. et al. 1993. *Proc. NIPR Symp. Antarct. Meteorites* **6**, 14–34. [6] Mikouchi T. 2001. Antarct. Meteorite Res., Vol. 14. 1-20 [7] Neal and Taylor. 1993. *Geochim.et Cosmo. Acta.* 56. 2177-2211 [8] Jolliff B.L et al. 2000. *JGR.* 105. 4197-4216. [9] Anders E. and Grevesse N. 1989. *Geochimica et Cosmochimica Acta.* 53, 97–214. [10] Joy et al. (2006) *Meteoritics & Planet. Sci.,* 41, 1003–1025 [11] Joy et al. (2006) LPS XXXVII #5221 [12] T. Arai et al., (2005) LPS XXXVI #2361.