RELATIONSHIPS AMONG SIX LUNAR METEORITES FROM MILLER RANGE, ANTARCTICA BASED ON COSMOGENIC RADIONUCLIDES.

K. Nishiizumi[1] and M. W. Caffee[2], [1]Space Sciences Laboratory, Univ. of California, Berkeley, CA 94720-7450, USA (kuni@ssl.berkeley.edu), [2]Dept. of Physics, Purdue Univ., West Lafayette, IN 47907, USA （mcaffee@purdue.edu).

Introduction: Six lunar meteorites were recovered from Miller Range (MIL) ice field by ANSMET during 2005, 2007, and 2009 field seasons: MIL 05035 (recovered mass: 142.2 g), MIL 07006 (1.4 g), MIL 090034 (195.6 g), MIL 090036 (245 g), MIL 090070 (137.5 g), and MIL 090075 (143.5 g). MIL 05035 is unbrecciated mare basalt. MIL 07006 and the four MIL 09 specimens are feldspathic regolith breccias. The petrographical and the chemical characteristics tentatively indicate they are not all paired [e.g., 1-4]. Using cosmogenic nuclides we are investigating the exposure histories and the pairing relationships of all six Miller Range lunar meteorites.

Cosmogenic nuclide studies of lunar meteorites contribute significantly to our understanding of these objects. Using a combination of cosmogenic stable- and radionuclides it is possible to determine a number of important properties of the meteorites. Most lunar meteorites have complex cosmic ray exposure (CRE) histories, having been exposed both at some depth on the lunar surface (2π irradiation) and after their ejection as small bodies in space during transport from the Moon to Earth (4π irradiation). Following these exposures is a period of residence on Earth's surface, a time commonly referred to as the terrestrial age. This terrestrial age varies, but the longest terrestrial age for a hot desert lunar meteorite is ~0.7 Myr [5]. Unraveling the complex history of these objects requires the measurement of at least four cosmogenic radionuclides. Noble gases in lunar meteorites also provide useful information on their exposure histories and conditions, in particular for samples having resided for a very long time in the lunar regolith. The specific goals of these measurements are to constrain the following shielding or exposure parameters: (1) the time a sample spent near the lunar surface; (2) the depth of the sample at the time of ejection from the Moon; (3) the transit time between lunar ejection and capture by Earth; and (4) the terrestrial age. The sum of the transit time and terrestrial age yields the ejection age, which is key to recognizing launch pairings of lunar meteorites. In this study, we measured cosmogenic radionuclides: ^{10}Be (half-life = 1.36 Myr), ^{26}Al (0.705 Myr), and ^{36}Cl (0.30 Myr) in 6 Miller Range lunar meteorites as well as NWA 7022 lunar meteorite as comparison, since it is similar in composition [6]. The ^{36}Cl measurements in MIL 09 meteorites are in progress.

Experimental Procedures and Results: In addition to their complement of galactic cosmic ray (GCR) produced nuclides many lunar meteorites contain nuclides produced by solar cosmic rays (SCR), which may further elucidate the shielding conditions of these meteorites *en route* to Earth. For each meteorite except MIL 07006, exterior and interior locations were sampled. The exterior samples from each were subdivided into smaller samples on the basis of their distance radially away from the fusion crust. In each case something of a depth profile was prepared. Each sample (28-127 mg) was dissolved in an HF/HNO$_3$ mixture in the presence of the Be and the Cl carrier solutions. After taking aliquots for chemical analyses by ICP-OES, Be, Al, Cl, Ca, and Mn were chemically separated and purified for AMS measurements. The ^{10}Be, ^{26}Al, and ^{36}Cl AMS measurements were performed at PRIME Lab, Purdue University.

Discussion: The ^{26}Al concentration in none of the exterior samples shows excess ^{26}Al due to SCR. This indicates that all Miller Range lunar meteorites were exposed to cosmic rays at a depth of more than a few cm.

MIL 05035. The ^{36}Cl activity in this meteorite is higher than the maximum allowable production rate of ^{36}Cl on the Moon (2π irradiation). Based on three cosmogenic nuclide concentrations, the most probable exposure scenario is that the MIL 05035 was ejected from deeper than 1,000 g/cm^2 of the Moon, followed by a transition time from the Moon to Earth of 0.68±0.13 Myr, which in turn was followed by a 70±60 kyr terrestrial residence. The preatmospheric radius was more than 5 cm. The ejection age of MIL 05035 is 0.75±0.14 Myr that is slightly shorter but overlaps with the ejection ages of Asuka 881757 (0.83±0.20 Myr) [7], Yamato 793169 (0.93±0.20 Myr) [7], and MET 01210 (0.96±0.13 Myr) [8]. The similarity of ejection ages supports launch pairing of these meteorites [9].

MIL 07006. The chemical composition and cosmogenic nuclide concentrations of MIL 07006 differ from the other MIL lunar meteorites. The petrography and detailed bulk chemical composition results indicate that MIL 07006 is not matched to other MIL lunar meteorites [e.g., 4]. It is difficult to estimate a unique exposure scenario of this meteorite based on only three cosmogenic nuclides although we can place limits on the possibilities. One is that the meteorite was ejected from a depth of about 100 g/cm^2 on the Moon and has 0.20±0.03 Myr terrestrial age. The transition time is much shorter than the half-lives of ^{10}Be and ^{26}Al. Another is that the meteorite was ejected from a depth greater than 1,000 g/cm^2 on the Moon and had transition time from the Moon to the Earth of 1.4±0.2 Myr followed by 0.30±0.05 Myr terrestrial age. The measurement of ^{41}Ca should further constrain the exposure condition.

MIL 090034/090070/090075. Petrographic and bulk chemical composition studies suggest paring of these 3 lunar meteorites [e.g., 1-4]. Our chemical analysis and the ^{10}Be and the ^{26}Al concentrations of these 3 meteorites also support pairing. Small variations of ^{10}Be (~30%) and ^{26}Al (~10%) can be explained by slightly different shielding depths and target element concentrations. Although we have only measured two nuclides at this time, if we assume these objects were exposed in space (4π) for more than a few Myr as 10-20 cm objects, we obtain a ~0.7 Myr terrestrial age. Since the chemical compositions of these meteorites are similar to Apollo 16 cores, we can directly compare the ^{10}Be and the ^{26}Al activities to those of the Apollo 16 cores [e.g., 10, 11]. An ejection depth of 10-60 g/cm^2 and short transition time fits both ^{10}Be and ^{26}Al profiles, although MIL 090034 might have been ejected from slightly deeper than MIL 090070.

MIL 090036. The ^{10}Be and ^{26}Al concentrations alone in this meteorite are also difficult to explain, assuming a 4π exposure in smaller body, without a long terrestrial age, similar to other MIL 09 meteorites. If the meteorite was exposed to cosmic rays on the Moon, the ejection depth is ~210 g/cm^2 followed by a short transition time and 0.1-0.2 Myr terrestrial age. Alternatively, one could propose the ejection of a large object (200-300 cm in radius) from >1,000 g/cm^2 depth for all MIL 09 lunar meteorites. This large object could then have a relatively long transit time, > a few Myr. The ^{10}Be and ^{26}Al activities in MIL 090034/70/75 are explained by exposure at 40-60 cm depth in this large object. For MIL 090036 the exposure depth is 100-130 cm. Based on both textures and mineral composition, NWA 7022 is suggested to be most similar to the MIL 090036 [6]. However, our ^{10}Be and ^{26}Al results do not support launch pairing of those two meteorites. Future measurements of additional nuclides will allow a more definitive assessment of the irradiation histories and pairing relationships.

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Table 1. Chemical compositions and cosmogenic radionuclide concentrations in Miller Range lunar meteorites.

MIL	Depth# (mm)	Mg (%)	Al (%)	K (ppm)	Ca (%)	Mn (ppm)	Fe (%)	Ni (ppm)	^{10}Be (dpm/kg)	^{26}Al (dpm/kg)	^{36}Cl (dpm/kg)	^{36}Cl*
05035,9	0-1	3.39	5.4	390	7.8	2460	18.68	6	5.89±0.11	52.1±1.4	14.36±0.33	17.52±0.41
05035,9	3-5	3.85	5.2	190	7.8	2450	16.54	13	5.79±0.06	52.9±1.7	14.51±0.40	18.24±0.50
05035,12	Int.	3.59	6.3	330	8.8	2240	15.30	15	5.93±0.11	53.4±1.3	14.75±0.32	17.09±0.37
07006,5	Int.	3.47	13.7	320	10.8	638	4.28	233	9.35±0.23	75.8±3.4	8.94±0.21	9.82±0.23
090034,13	0-1	1.58	15.1	750	11.6	396	2.58	27	10.44±0.09	64.0±2.8		
090034,13	4-6	1.65	15.6	440	11.8	400	2.64	45	9.78±0.14	65.2±1.9		
090034,18	0-2	1.74	15.4	470	11.6	381	2.52	38	9.86±0.17	67.3±2.3		
090034,18	4-8	1.60	15.3	590	11.7	387	2.45	48	10.13±0.10	67.2±2.4		
090034,12	Int.	1.59	15.8	200	11.7	383	2.58	35	9.87±0.09	71.8±2.5		
090036,12	0-2	2.12	15.0	990	11.2	321	2.35	207	5.45±0.09	25.9±0.9		
090036,13	Int.	2.60	14.4	930	10.6	415	3.21	147	4.85±0.04	27.4±1.5		
090070,12	0-1	1.67	15.6	1400	11.4	381	2.43	29	13.32±0.13	64.1±2.3		
090070,12	3-4	1.62	15.8	480	11.4	380	2.44	44	11.90±0.11	68.7±2.8		
090070,21	0-1.5	1.57	15.6	1200	11.3	378	2.32	27	14.22±0.13	68.4±2.0		
090070,21	3-5	1.71	15.8	390	11.4	377	2.47	46	13.03±0.21	64.8±2.4		
090070,14	Int.	1.71	16.0	310	11.5	381	2.51	48	11.51±0.17	71.2±2.9		
090075,12	0-1.5	1.75	15.3	1570	10.9	409	2.58	32	13.10±0.19	70.2±2.8		
090075,13	0-1.5	1.51	15.2	1840	10.9	395	2.58	32	11.46±0.15	66.0±3.1		
090075,18	Int.	1.67	15.8	300	11.5	363	2.44	66	9.46±0.08	67.5±3.3		
NWA 7022		3.01	13.3	1120	9.7	481	3.51	165	0.33±0.01	6.9±0.3		

#depth from fusion crust, Int:interior sample, *dpm/kg (8Ca+Fe)