EXPOSURE HISTORY OF LUNAR METEORITE NORTHWEST AFRICA 5000. K. Nishiizumi[1], M. W. Caffee[2], N. Vogel[3], R. Wieler[3], M. D. Leclerc[4], and A. J. T. Jull[4], [1]Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA (kuni@ssl.berkeley.edu), [2]Department of Physics, Purdue University, West Lafayette, IN 47907-1396, USA (mcaffee@purdue.edu), [3]ETH-Zürich, CH-8092, Switzerland (vogel@erdw.ethz.ch, wieler@erdw.ethz.ch), [4]NSF Arizona AMS Facility, University of Arizona, Tucson, AZ 85721, USA (leclerc@email.arizona.edu, jull@email.arizona.edu).

Introduction: A lunar meteorite Northwest Africa 5000 (NWA 5000) was found in southern Morocco in 2007. The recovered mass and size of the meteorite, 11.528 kg and 27 x 24 x 20 cm, respectively, make it the second largest known lunar meteorite [1]. The meteorite is a highland feldspathic leucogabbroic breccia. It does not appear to be paired with any other NWA lunar meteorites [1, 2].

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 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. The maximum terrestrial age for hot desert meteorites was found to be ~0.6 Myr [3]. 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 had spent near the lunar surface; (2) the depth of the sample at the time of ejection from the Moon; (3) the transit time from ejection off the lunar surface until capture by Earth; and (4) the terrestrial age. The sum of the transit time and terrestrial age yields the ejection age, which is critical to recognize launch pairing of lunar meteorites. The ejection age, in conjunction with the sample depth on the Moon, can then be used to model impact and ejection mechanisms. In this study, we measured cosmogenic radionuclides and noble gases in NWA 5000.

Experimental Procedures:

^{10}Be, ^{26}Al, ^{36}Cl, and ^{41}Ca measurements. We received an exterior chip with white and brownish terrestrial weathering products. To eliminate them, the sample was leached twice with a 1.5 N HNO_3 solution in an ultrasonic bath for 15 and 10 minutes. The weight loss was 23%, indicating severe terrestrial contamination. Although this lunar meteorite is not heavily weathered and it seems to be relatively fresh our fragment had considerable terrestrial contamination and is one of the most contaminated we have studied. 70.1 mg of ground sample was dissolved in an HF-HNO_3 mixture along with Be and Cl carriers. Be, Al, Cl, and Ca were separated for accelerator mass spectrometry (AMS) measurements. The ^{10}Be and ^{36}Cl AMS measurements were performed at PRIME Lab, Purdue University. Measurements of ^{26}Al and ^{41}Ca are in progress.

^{14}C measurement. Samples were pretreated with 100% H_3PO_4 to remove weathering products. The residue was then washed and dried before melting in a flow of oxygen to recover $^{14}CO_2$ in presence of a carrier. 97.4 mg of NWA 5000 was used for the ^{14}C measurements. The AMS measurements were performed at the University of Arizona NSF-AMS facility.

Noble gas measurements. A chip of 92 mg was pre-heated in vacuum at ~120°C over night. Noble gases were released in a single step at 1800°C, followed by mass spectrometric analyses of He, Ne, and Ar according to procedures outlined in ref. [4].

Results and Discussion: Preliminary results of ^{10}Be, ^{14}C, and ^{36}Cl concentrations ($\pm 1\sigma$) in NWA 5000 are shown in Table 1. Preliminary concentrations and isotopic compositions of He, Ne, and Ar are shown in Table 2.

Radionuclides. A maximum ^{14}C terrestrial age of 10.4 ± 1.3 kyr was calculated assuming the ^{14}C was produced entirely by a 4π exposure during the Moon-to-Earth transit; a ^{14}C saturation activity of 65 dpm/kg was also assumed. This short terrestrial age produces negligible decay corrections for ^{36}Cl (< 2%) and ^{10}Be (< 1%). If all cosmogenic radionuclides were produced by build-up during a 4π exposure, a minimum ^{14}C exposure age would be 2.8 kyr. Likewise, the ^{36}Cl and ^{10}Be ages would be 80 kyr and 310 kyr, respectively. The large discrepancy between 4π exposure ages implies that a large portion of the ^{36}Cl and ^{10}Be was produced on the Moon during a 2π exposure before the ejection. The end-member exposure model in which all cosmogenic nuclides are produced in space would not be correct. The alternative end-member model is that most of the inventory of long-lived cosmogenic nuclides was produced on the lunar surface. Production rates as a function of depth on the Moon are required to determine a 2π regolith exposure; these are typically obtained from comparison of the measured activities to those in the Apollo 15 drill core, which extends to a depth of about 400 g/cm^2. We compared measured ^{10}Be and ^{36}Cl activities to those of the Apollo 15 drill core depth profiles [5], normalizing for differences in the target elemental composition. The measured activities match the production at 325 ± 20 g/cm^2 for ^{10}Be and 350 ± 40 g/cm^2 for ^{36}Cl. The measured ^{14}C activities are also compared to the Apollo 15 drill core [6]. The observed ^{14}C activity is equivalent to a much shallower depth of 245 ± 15 g/cm^2. The ^{14}C activity can be reconciled with the ^{10}Be- and ^{36}Cl-derived ejection depth of 335 ± 20 g/cm^2, and with the assumption that the balance of the ^{14}C was produced during the post-ejection 4π exposure. For this exposure scenario, the minimum 4π exposure age is 1.3 kyr, assuming negligible terrestrial age.

Noble gases. NWA 5000 contains substantial amounts of solar noble gases as demonstrated by the isotopic ratios ^{3}He/^{4}He, ^{20}Ne/^{22}Ne and ^{36}Ar/^{38}Ar, which are all typical for solar gas-rich lunar regolith samples (Table 2). Elemental ratios (^{4}He/^{20}Ne = 14.3; ^{20}Ne/^{36}Ar = 3.70) are typical for plagioclase-rich samples, which have poor retentivity for solar He and Ne [7]. Much of the measured ^{40}Ar is likely radiogenic, hence the ^{40}Ar/^{36}Ar ratio cannot be used to constrain the time of solar-wind implantation ("antiquity") of the sample. The regolithic origin of NWA 5000 is in agreement with observations on other lunar meteorites [8] and suggests by itself a shallow depth of ejection.

The solar He and Ar inhibit a determination of cosmogenic ^{3}He and ^{38}Ar (although the rather high measured ^{3}He/^{4}He ratio suggests that a sizeable fraction of the ^{3}He is cosmogenic). The concentration of cosmogenic ^{21}Ne is 1.57x10^{-7} cm^3 STP/g (assuming trapped Ne composition to fall in-between the pure and fractionated SW end-members [e. g., 9]. This value is typical for lunar meteorites [8]. Obviously, most of the cosmogenic ^{21}Ne in NWA 5000 was produced on the lunar surface. Taking the ^{21}Ne production rate on the lunar surface of 0.051x10^{-8} cm^3 STP/(g·Myr) given in [8] for lunar highland breccia Dhofar 081 (with 180 g/cm^2 shielding depth) and correcting for the larger shielding experienced by NWA 5000 results in a P(^{21}Ne) value of about 0.02x10^{-8} cm^3 STP/(g·Myr). This yields a residence time on the lunar surface of NWA 5000 of about 600 Myr, if we assume that throughout its entire regolith history the sample resided at the same depth as during the past few Myr before ejection. Such a long pre-exposure time on the lunar surface is again typical for lunar meteorites.

Table 1. Cosmogenic radionuclide in NWA 5000.

Nuclide	half-life (yr)	dpm/kg
^{10}Be	1.36x10^6	2.93 ± 0.03
^{14}C	5,730	18.6 ± 0.6
^{36}Cl	3.0x10^5	3.94 ± 0.13

Table 2. He, Ne, and Ar in NWA 5000.

^{4}He	^{3}He/^{4}He	^{20}Ne	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne
156.3	4.31x10^{-4}	10.91	12.44	0.0486

^{36}Ar	^{40}Ar/^{36}Ar	^{36}Ar/^{38}Ar
2.950	4.307	5.107

Gas concentrations in 10^{-5} cm^3 STP/g
Uncertainties: 4% for concentrations, 3% for ^{3}He/^{4}He, 1% for other isotope ratios

Based on ^{10}Be, ^{14}C, ^{36}Cl and cosmogenic ^{21}Ne concentrations, the most likely exposure history of NWA 5000 was as follows: After a roughly 600 Myr residence in the lunar regolith, the meteorite was ejected from a depth of 335 ± 20 g/cm^2 on the Moon. The minimum transition time from the Moon to Earth was 1.3 kyr with only a short terrestrial age < 1 kyr. The short terrestrial age is consistent with the presence of fresh, translucent fusion crust on part of the meteorite [1]. We cannot completely rule out a longer terrestrial age up to ~10.4 kyr. ^{26}Al and ^{41}Ca measurements are required to further constrain the history. Although the petrologic observation and the trace element chemical compositions [1, 2] do not support pairing, the exposure history of NWA 5000 is similar to that of NWA 3163 [10].

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References: [1] Irving A. J. et al. (2008) *LPS XXXIX,* Abstract #2168. [2] Korotev R. L. et al. (2008) *LPS XXXIX*, Abstract #1209. [3] Nishiizumi K. et al. (2002) *LPS XXXIII*, Abstract #1366. [4] Wieler R. et al. (1989) *GCA, 53,* 1449-1459. [5] Nishiizumi K. et al. (1984) *EPSL, 70,* 157-163. [6] Jull A. J. T. et al. (1998) *GCA, 62,* 3025-3036. [7] Signer P. et al. (1977) *Proc. Lunar Sci. Conf., 8th,* 3657-3683. [8] Lorenzetti S. et al. (2005) *Meteoritics & Planet. Sci.*, *40,* 315-327. [9] Grimberg A. et al. (2008) *GCA, 72,* 626-645. [10] Nishiizumi K. and Caffee M. W. (2006) *Meteoritics & Planet. Sci., 41,* A133.