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EXPOSURE HISTORIES OF LUNAR METEORITES NORTHWEST AFRICA 032 AND DHOFAR 081.

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Introduction: Recent additions to the list of lunar meteorites include Northwest Africa (NWA) 032 and Dhofar 081. NWA 032 is an unbrecciated basalt, found in Morocco; Dhofar 081 is a fragmented feldspathic breccia, found in Oman. Our goal is the determination of the cosmic ray exposure history of these objects. Most lunar meteorites have complex cosmic ray exposure histories, having been exposed both at some depth on the lunar surface (2π irradiation) before their ejection and as small bodies in space (4π irradiation) during transport from the Moon to the Earth. These exposures were then followed by residence on the Earth's surface, the terrestrial residence time. Unraveling the complex history of these objects requires the measurement of at least four cosmogenic nuclides. The specific goals of these measurements are to constrain the depth of the sample at the time of ejection from the Moon, the transit time from the time of ejection to the time of capture by the Earth, and the residence time on the Earth's surface. These exposure durations in conjunction with the sample depth on the Moon can then be used to model impact and ejection mechanisms. To investigate the complex exposure histories of lunar meteorites, we measured cosmogenic nuclides, ^{36}Cl (half-life = 3.01×10^5 yr), ^{26}Al (7.05×10^5 yr), and ^{10}Be (1.5×10^6 yr) in NWA 032 and Dhofar 081. The measurements of ^{41}Ca (1.04×10^5 yr) are in progress.

Sample Description: The recovered mass of NWA 032 is ~300 g and it is covered by fusion crust. The recovered mass of Dhofar 081 is 174 g and in size it is ~4.5x4x4.5 cm; it is covered by fusion crust. Since some lunar meteorites, specifically Calcalong Creek, Y-791197, Y-793169, and QUE 93069/94269 contain SCR (solar cosmic ray) produced nuclides [e. g. 1, 2], which indicate negligible ablation during atmospheric entry, searching for SCR effects is an important component of this study. SCR-produced nuclides exhibit strong depth dependence so we measured cosmogenic radionuclides in 2 sub-samples having different shielding depths for both NWA 032 and Dhofar 081. The exterior samples of both meteorites are covered with fusion crust. Two samples of NWA 032 were chipped from a 4.5x6.7 cm slab. The interior sample was obtained from near center of the slab. The exterior sample is covered by the fusion crust and the entire sample is less than 1.5 mm from the surface. The distance between the exterior and interior samples of NWA 032 is 2.5 cm; for Dhofar 081 this distance is ~1.5 cm.

Experimental Procedures and Results: To eliminate weathering products each sample was etched twice with 0.2 N HNO_3 solution in an ultrasonic bath for 15 minutes; the weight loss from this procedure is 1.3-2.8%. Each sample was then dissolved in an HF-HNO_3 mixture along with Be and Al carriers. The concentrations of Mg, Al, Ca, Mn, and Fe in the samples were determined by atomic absorption spectroscopy. The AMS measurements were performed at the Lawrence Livermore National Laboratory. The preliminary radionuclide data are shown in Table 1. The quoted errors represent $\pm1\sigma$ AMS measurement error.

NWA 032: The concentrations of ^{10}Be in NWA 032 are extremely low, indeed, among the lowest measured in lunar meteorites. The low concentrations of all measured spallation products, ^{10}Be, ^{26}Al, and ^{36}Cl, indicate that the integrated exposure of this sample to GCR is minimal. The cosmogenic nuclides observed in this sample could have been produced during the sample's residence in the lunar surface or during its transition time between the Moon and Earth, or a combination of both. With the nuclides measured to date we can test two scenarios: production of the cosmogenic nuclides at depth in the lunar regolith; and production of the cosmogenic nuclides after ejection from the lunar surface during the short transition between the Moon and Earth.

2π exposure: Production rates are required to determine a regolith exposure age; these are typically obtained from comparison of the measured activities to those in the Apollo 15 drill core, which extend to a depth of about 400 g/cm^2 [3, 4]. However, the nuclide concentrations in NWA 032 are lower than the values associated with the deepest samples in the Apollo 15 drill core, indicating exposure at a greater depth. Production rates for burial deeper than 400 g/cm^2 were calculated using two methods [5]. The first uses the theoretical GCR production rate calculation as given by the LAHET Code System (LCS) [6]. The second method employs an extrapolation of the Apollo 15 depth profile to below 400 g/cm^2. Differences in target chemistry were accounted for by normalizing the observed nuclide concentrations in the NWA 032 to those of the Apollo 15 core chemical composition. The elemental production ratios were calculated using LCS. The measured radionuclide concentrations in NWA 032 correspond to exposure at depths of 660-730 g/cm^2 for ^{10}Be, 520-630 g/cm^2 for ^{26}Al, and 520-540 g/cm^2 for ^{36}Cl. Clearly the three nuclides do not yield a unique exposure depth. Although many lunar meteorites do not indicate production of all radionuclides at a unique depth, the shorter half-life nuclides indicate production at a greater depth. This circumstance arises because of the faster decay of these nuclides during terrestrial residence [e. g. 1]. For NWA 032 the shorter half-life nuclides indicate less shielding. Al-

though we cannot rule out the possibility that some fraction of the radionuclides in NWA 032 were produced in the regolith, the data are inconsistent with the production of most of the cosmogenic nuclides in the lunar regolith.

4π exposure: The ^{26}Al activity in the exterior sample of NWA 032 is 50 % higher than that of the interior sample. If this excess ^{26}Al is SCR produced, it is necessarily produced during the 4π irradiation in space. The production rate of SCR-produced ^{26}Al is strongly dependent on depth and the object's size in space. Since SCRs produce nuclides in only the upper few cm, the preatmospheric radius of NWA 032 must be 4-7 cm, assuming nominal ablation of material during atmospheric entry. The GCR production rates of ^{10}Be, ^{26}Al, and ^{36}Cl in objects having radii of 4 and 6 cm were calculated by LCS [6]. The 4π-exposure age, i.e. the transition time from the Moon to Earth, is 0.042±0.008 Myr for ^{10}Be and 0.042±0.003 Myr for ^{36}Cl. The ^{26}Al ages (interior sample) are 0.064±0.007 Myr for a 6 cm radius and 0.077±0.008 Myr for 4 cm radius. The longer ^{26}Al exposure age may be the result of production of some ^{26}Al by SCRs in interior sample. Although the experimental error of ^{10}Be is large, the ^{10}Be exposure age is robust because ^{10}Be is exclusively produced by GCR. The excess ^{26}Al that was produced by SCRs is 0.5-1 dpm for the interior sample and 2.1-2.6 dpm for the exterior sample assuming a 0.042 Myr exposure age and a preatmospheric size of 4 and 6 cm in radius. The saturation values of SCR produced ^{26}Al for these radii are 12-25 dpm and 50-65 dpm respectively. The latter value is similar to the SCR production rate for ^{26}Al at a depth of ~1 cm in an object having a radius of 3-4 cm [7, 8]. A coherent self-consistent model for the irradiation history of NWA 032 is (1) a 0.042 Myr transition time from the Moon to Earth, (2) a preatmospheric size of less than 5 cm radius, (3) ~1 cm of ablation during atmospheric entry, and (4) a terrestrial residence time of < 80 kyr. The ejection depth was more than 1100 g/cm^2 on the Moon. The measurements of cosmogenic nuclides in opposite side of exterior sample will further constrain the exposure history of NWA 032. Although this scenario is consistent with the available data other more complex scenarios can only be eliminated from consideration with the measurement of ^{14}C and ^{41}Ca.

Dhofar 081: Since the chemical composition of Dhofar 081 is comparable to that of MAC 88104/88105 and QUE 93069/94269, ^{10}Be, ^{26}Al, and ^{36}Cl averages from these samples [1] [2] are shown in Table 1 in addition to the measurements from Dhofar 081. It is interesting to note that the elemental abundances of solar noble gases of Dhofar 081 are similar to those of MAC 88104 [9]. The ^{10}Be, ^{26}Al, and ^{36}Cl concentrations in both the interior and exterior samples of Dhofar 081 are identical. The lack of excess ^{26}Al in the exterior samples relative to the interior samples clearly shows no SCR effects. Furthermore, the lack of a gradient in cosmogenic nuclide concentrations as a function of depth indicates that most of the cosmogenic nuclides were produced at some depth on the Moon during a 2π exposure geometry. This conclusion is supported by discordance among model 4π-exposure ages based on the three measured nuclides. Evidently, the transition time between the Moon and Earth was too short for the production of detectable amounts of long-lived nuclides. The ^{10}Be, ^{26}Al, and ^{36}Cl concentrations of Dhofar 081 are about midway between the extremes observed in MAC 88104/88105 and QUE 93069/94269. The ^{10}Be, ^{26}Al, ^{36}Cl concentrations in Dhofar 081 were normalized to Apollo 15 drill core chemical composition as described above. The normalized nuclide concentrations correspond to exposure at 205-220 g/cm^2 for ^{10}Be, 240-260 g/cm^2 for ^{26}Al, and 280-300 g/cm^2 for ^{36}Cl. Correcting for a terrestrial age of 200 kyr, the ^{10}Be, ^{26}Al, and ^{36}Cl are all consistent with ejection from a depth of 190-210 g/cm^2. The ^{41}Ca measurement as well as ^{14}C will further constrain the ejection depth and provide a direct measurement of the terrestrial age of Dhofar 081.

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Table 1. Cosmogenic radionuclide concentration (dpm/kg meteorite) in NWA 032 and Dhofar 081.

	Mass (mg)	^{10}Be	^{26}Al	^{36}Cl	^{36}Cl*
NWA 032 (interior)	37.6	0.32±0.07	2.9±0.3	1.30±0.04	1.32±0.04
NWA 032 (exterior)	23.6	0.40±0.11	4.4±0.3	1.39±0.05	1.35±0.04
Dhofar 081 (interior)	63.1	5.18±0.09	31.9±0.9	7.40±0.12	5.54±0.09
Dhofar 081 (exterior)	64.9	5.38±0.09	31.2±0.8	7.16±0.11	5.68±0.09
MAC 88104/88105	average	2.25±0.25#	16.4±3.2#	3.43±0.14#	2.73±0.17
QUE 93069/94269	average	11.96±0.35@	72.1±3.2@	14.0±0.9@	11.8±0.8

*dpm/kg (10Ca+Fe); # [1]; @ [2]

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