EXPOSURE HISTORIES OF DAR AL GANI 262 LUNAR METEORITES. K. Nishiizumi[1], M. W. Caffee[2], and A. J. T. Jull[3], [1]Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, kuni@ssl.berkeley.edu, [2]Geoscience and Environmental Technology, Lawrence Livermore National Laboratory, Livermore, CA 94550, caffee1@llnl.gov, [3]NSF AMS Facility, University of Arizona, Tucson, AZ 85721, ajtjull@rvax.ccit.arizona.edu

A polymict anorthositic lunar highland breccia, Dar al Gani 262 was found March 23, 1997 in the Libyan part of the Sahara [1, 2]. This piece is the sixteenth individual lunar rock representing twelve lunar meteorites. The recovered weight is 513 g. We received three subsamples from Dr. A. Bischoff for this study. We report here preliminary results of cosmogenic ^{14}C (half-life = 5730 y), ^{36}Cl ($3.01x10^5$ y), ^{26}Al ($7.05x10^5$ y), and ^{10}Be ($1.5x10^5$ y) for this meteorite.

Most lunar meteorites have complex cosmic ray exposure histories, having been exposed both at some depth on the Moon (2 irradiation) before their ejection and as small bodies in space (4 irradiation) during transport from the Moon to the Earth [e.g. 3, 4]. These exposures are then followed by residence on the Earth's surface, the terrestrial residence time. To quantify the complex histories of these objects cosmogenic radio- and stable nuclides will be measured. The concentrations of cosmogenic nuclides also constrain the depth of the sample at the time of ejection from the Moon. Generally, unraveling the complex history of these objects requires the measurement of at least four cosmogenic nuclides. These exposure durations in conjunction with the sample depth on the Moon can then be used to model impact and ejection mechanisms.

Since some lunar meteorites, specifically Calcalong Creek, Y-791197, Y-793169, and QUE 93069/94269 contain SCR (solar cosmic ray) produced nuclides [4-6], which indicate negligible ablation during atmospheric entry, searching for SCR effects is an important component of this study. To investigate SCR effects in Dar al Gani 262, we measured ^{10}Be, ^{26}Al, and ^{36}Cl in 2 sub-samples having different shielding depths. An exterior sample was collected from the surface of meteorite. The interior sample was collected from about 1 cm deeper than the exterior sample. A sample for ^{14}C measurement was also collected from within 1 cm from the surface.

The concentrations of Mg, Al, K, Ca, and Fe in aliquots of interior and exterior samples were determined by atomic absorption spectroscopy. The results are shown in Table 1. The AMS measurements were performed at the Lawrence Livermore National Laboratory (^{10}Be, ^{26}Al, ^{36}Cl) and at the University of Arizona NSF-AMS facility (^{14}C). The preliminary results are shown in table 2.

No detectable amount of ^{14}C, < 1 dpm/kg, was observed, indicating a long terrestrial age. Depending on whether the object was exposed in a 2 or 4 exposure geometry, the ^{14}C terrestrial age is calculated to be > 27 ky or > 32 ky, respectively. This terrestrial age is longer than the average terrestrial ages of other meteorites found in the Libyan portion of Sahara desert [7].

The ^{10}Be and ^{36}Cl concentrations in interior and exterior specimens are identical. The few percent difference of ^{26}Al concentrations between the two samples is due to the chemical heterogeneity. No excess of ^{26}Al in the exterior sample compare to the interior sample clearly shows no SCR effect on this meteorite. This clearly indicates that either the ablation depth is more than a few cm or the meteorite was ejected from more than 12-15 g/cm^2 depth on the Moon and did not have a long transition from the Moon to Earth.

Since the terrestrial age cannot be uniquely determined as yet and there is a possibility that it is long enough to effect ^{36}Cl concentrations it is necessary to consider the relative merits of two distinct irradiation scenarios.

4 exposure case: Some lunar meteorites, such as Y-82192/82193/86032, Y-793169, Calcalong Creek, and A-881757 have a transition time of more than 1 My in a 4 geometry [e.g. 3, 5]. Correspondingly, if all cosmogenic radionuclides, ^{10}Be, ^{26}Al, and ^{36}Cl in Dar al Gani 262 were produced during the transition from the Moon to the earth in a 4 geometry by GCR (galactic cosmic rays), the meteoroid would necessarily be small (less than several cm radius), and possess a short exposure age (~2 My). Additionally, the required terrestrial age for this scenario would be ~200 ky. However, in such a small meteoroid there would most likely be SCR produced ^{26}Al resulting in a steep gradient in the ^{26}Al production rates over cm distances. No gradient in ^{26}Al activity is observed therefore this particular irradiation scenario is unlikely.

2 exposure case: The noble gas and nitrogen isotopic compositions and concentrations clearly indicate that Dar al Gani 262 is not only lunar in origin but also that it resided on the surface of the Moon [2]. Although the exposure age on the Moon cannot be calculated from the cosmogenic noble gas concentration because of uncertainties in the depth for the integrated exposure, the exposure time is much longer than the half-lives of cosmogenic radionuclides. The determination depth using cosmogenic nuclides requires production rates. In lunar meteorites, the 2 production rates of cosmogenic nuclides are calculated using the observed production profiles in Apollo 15 drill core, measured target elemental compositions, and the Reedy-Arnold theoretical production model [8-10]. The recent measurements of various cross sections coupled with the development of theoretical GCR particle calculation methods has improved the production rates calculation of cosmogenic nuclides in both meteorites and lunar samples. For example, Reedy and Masarik's GCR production rate calculation with LAHT Code System (LCS) agrees with the measurements of some cosmogenic nuclides in Apollo 15 long core (15001-6) [11]. However, the model calculation does is not consistent with cosmogenic radionuclide concentrations in some lunar cores having different chemical compositions. The problem is most pronounced with production of ^{26}Al and ^{36}Cl. In these cases the problem is most likely the lack of high energy neutron cross sections. The major target elemental composition of Dar al Gani 262 differs significantly from that of Apollo 15 core. The chemical composition of Dar al Gani 262 is however similar to the Apollo 16 drive tube 60010/9. The LCS-calculated GCR production rates [J. Masarik, priv. comm.] of ^{26}Al and ^{36}Cl in the Apollo 16 drive tube differ from the measured values in the Apollo 16 core. For ^{10}Be the calculated production rates are in good agreement with measurements. In this study, we adopt the observed activities of ^{10}Be, ^{26}Al, and ^{36}Cl in 60010/9 as 2 production rates between 23 and 75 g/cm^2. This approach is similar to that used for QUE 93069/94269 [6]. The chemical composition and cosmogenic nuclide concentration for three different depths of the Apollo 16 drive tube are shown in Table 3. The Al concentration in 60010/9 is slightly higher than that of Dar al Gani 262. Since Al and Si are major target element of production of ^{26}Al, a small correction was applied to the observed values. Assuming constant Si and 13.7 % Al (Dar al Gani 262) concentration, the production rates of ^{26}Al are to be 70, 66, and 58 atom/min·kg at 23, 51, and 75 g/cm^2. The ^{36}Cl activities are normalized to chemical composition and expressed as dpm/kg (32K+8Ca+Fe) as shown in Table 2 and 3.

The observed activities in Dar al Gani 262 are consistent with a depth of 80-100 g/cm^2 for ^{10}Be, 85-110 g/cm^2 for ^{26}Al, and 110-130 g/cm^2 for ^{36}Cl. This depth estimation is inheritantly uncertain owing to extrapolation of Apollo 16 core data. The offset in the depth estimate toward deeper values with decreasing radionuclide half-life is observed in other lunar meteorites. This effect is due to decay of the radionuclide during terrestrial residence [4]. For Dar al Gani 262, the best fit to the available data requires an ejection from 75-85 g/cm^2 and a 50-60 ky terrestrial age. In this model, the transition time is negligible and accordingly produces insignificant cosmogenic nuclides in space.

Although the combination of a long 2 exposure on the Moon followed by a short 4 exposure during transition from the Moon to the earth results in the observed cosmogenic nuclide pattern, a more definitive exposure scenario awaits measurement of ^{41}Ca (half-life = 1.0x10^5 y) in the near future.

Bischoff et al [2] also reported ^{53}Mn, ^{10}Be, and ^{26}Al in Dar al Gani 262. The ^{10}Be result is are in good agreement with ours but their ^{26}Al value, 72±4 dpm/kg, is ~25 % higher than our measurement even after taking into account the slightly different Al concentration. The high ^{26}Al concentration corresponds to ~20-30 g/cm^2 shielding on the moon based on our lunar core 60010/9 results. This depth, based on ^{26}Al, does not agree with ^{10}Be depth. Furthermore, the observed ^{53}Mn (half-life=3.7x10^6 y) activity, 326±48 dpm/kg Fe [2], can only explained by SCR production on the Moon (less than 15 g/cm^2 depth) or during a 4 exposure in space. If the high ^{53}Mn and ^{26}Al were produced by SCR on the moon, the sample of Bischoff et al should be displaced by ~60 g/cm^2 (~20 cm) from our sample. However, the small recovered mass of the meteorite eliminates this possibility. On the other hand, the ^{53}Mn-^{10}Be pair excludes a simple 4 exposure. A possible resolution is a scenario in the meteorite was ejected from a depth of ~50 g/cm^2 on the Moon, had a transition time of ~0.5 My, followed by a terrestrial residence of ~0.3 My. Our sample was then exposed at more than a few cm depth in the meteoroid and the other sample [2] was exposed on the surface to SCR during 4 irradiation. In this model, our sample and the other sample are displaced by more than few cm. Clearly, the data just barely allow this scenario.

This meteorite contain significant amount of terrestrial weathering products [1, 2]. High Cl (370 ppm) was found in the meteorite [2]. In this study, we neglect the production of ^{36}Cl by ^{35}Cl(n,γ) reaction. If we adopt the high Cl value, the ^{36}Cl production rate by spallation and thermal neutron capture at near 80 g/cm^2 is 45-50 atom/kg·min, far higher than the observed value. Therefore majority of Cl in the meteorite is terrestrial contamination.

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Table 1. Chemical composition of Dar al Gani 262.

	Wt (mg)	Mg (%)	Al (%)	K (ppm)	Ca (%)	Fe (%)
interior	32.26	2.85	14.0	510	11.6	3.07
exterior	28.20	2.85	13.3	500	10.8	3.30

Table 2. Cosmogenic radionuclide concentration (dpm/kg meteorite) in Dar al Gani 262.

	^{10}Be	^{26}Al	^{36}Cl	^{36}Cl/(32K+8Ca+Fe)	^{14}C
interior					< 1
interior	10.90±0.20	57.2±1.7	13.65±0.37	14.0 ± 0.4	
exterior	11.13±0.30	54.6±1.6	13.74±0.17	15.1 ± 0.2	

Table 3. Chemical composition and cosmogenic radionuclide in Apollo 16 double drive tube.

	Depth (g/cm^2)	Mg (%)	Al (%)	K (ppm)	Ca (%)	Fe (%)	^{10}Be (dpm/kg)	^{26}Al (dpm/kg)	^{36}Cl (dpm/kg)	^{36}Cl*
60010,3234	23.1	3.40	14.9	1140	11.1	4.01	13.32±0.42	73.5±1.6	16.23±0.47	16.8±0.5
60009,3271	50.7	3.21	15.0	1010	11.3	3.79	12.89±0.40	69.5±1.9	17.15±0.40	17.6±0.4
60009,3273	74.9	2.08	17.0	540	12.4	2.32	11.25±0.32	66.4±1.4	17.04±0.46	16.5±0.4

*dpm/kg (32K+8Ca+Fe)