LUNAR REGOLITH ACTIVITY INFERRED FROM COSMOGENIC RADIONUCLIDES ^{26}Al AND ^{36}Cl IN CORE 60014/60013.

S. A. Binnie[1], K. Nishiizumi[1], K. C. Welten[1] and M. W. Caffee[2]. [1]Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA (sbinnie@uni-koeln.edu), [2]PRIME Lab., Purdue University, West Lafayette, IN 47907-1306, USA.

Introduction: The processes of lunar regolith mixing and transport are poorly understood. Measuring cosmic-ray-produced (cosmogenic) nuclide profiles in lunar cores provides a direct means to investigate the processes operating at the lunar surface. To study regolith activity we measured cosmogenic ^{26}Al ($t_{1/2}$= 0.705 Myr) and ^{36}Cl ($t_{1/2}$= 0.301 Myr) from Apollo 16 double drive tube core 60014/60013. We compare our results to predicted ^{26}Al and ^{36}Cl production rates and consider processes of regolith reworking. The ^{10}Be ($t_{1/2}$= 1.36 Myr) measurements from the cores are in progress.

Core Descriptions: Core 60014/60013 was collected ~75 m SW of the Apollo 16 lunar module landing site, ~4.5 km S of North Ray crater and the Smoky Mountains. This core was one of three from this station, each around 50 m apart in a triangular sampling array; 60001-7 and 60009/60010 are the other two. The motivation for spacing these three cores in this way was to collect typical Cayley Plains material and investigate the lateral as well as vertical stratigraphy of the lunar regolith. It was also considered that regolith cores from this location may incorporate ejecta from both the South Ray and North Ray impact events. The core sampled a regolith surface where, unlike other Apollo 16 core sites, small craters were scarce. However, larger craters (10 – 20 m scale) are more prevalent here than at other stations, and there is a relative abundance of 20 – 50 cm cobbles on the surface [1].

The core lengths are 28.2 cm (60014, upper part of the core; [2]) and 33.7 cm (60013, lower part of the core; [3]), with respective densities of 1.48 and 1.63 g/cm^3 and an overall recovery of 90% [1]. A void was found in the top 4 cm of core 60014, and the top 5 cm was loosely packed and less coherent than the material below it [2]. Hörz et al. [1] tentatively assigned the 60014/60013 core 9 discrete units based on X-radiography. Korotev et al. [4] found around 3 compositionally distinct units, decreasing in maturity with depth based on I_s/FeO data. This pattern of decreasing maturity is also supported by agglutinate contents [5].

Methods and Results: We prepared splits of 18 samples (50-70 mg) from the length of the cores according to [6], and measured cosmogenic radionuclides by AMS at PRIME-Lab, Purdue University. To compare the measured radionuclide concentrations and steady-state production rate profiles we normalize the ^{26}Al and ^{36}Cl results of the Apollo 15 deep drill core [6,7], core 15008 [8] and Apollo 16 surface rock 64455 [9] to our results from core 60014/60013, following [6]. The cosmogenic radionuclide depth profiles of Apollo 15 deep drill cores indicate that they have been collected from a non-mixed regolith that has been stable over tens of millions of years, and so provide the best estimates for ^{26}Al, ^{36}Cl, and ^{10}Be production rate profiles by galactic cosmic rays (GCR). The production rate estimates in rock sample 64455 as well as the top layers of core 15008 account for the solar cosmic ray (SCR) contribution to the production of radionuclides in the near surface. We also normalize the 60014/60013 data for the slight elemental variations along the core length. This changes the concentrations of ^{36}Cl by <3% and ^{26}Al by <2%. The mean concentrations of the main target elements in the core are Fe = 4.0%; Ca = 10.6%; K = 0.1%; Si = 22.4%; Al = 13.9%; O = 43.1 %. The results for two ^{36}Cl measurements (those at depths of ~2 and ~18 g/cm^2) are pending. The variability in our cosmogenic nuclide activity measurements with depth are shown in figures 1A and 1B, alongside the production profiles expected of a stable regolith.

Discussion: The ^{36}Cl concentrations in 60014/60013 show more variability than is predicted by the production rate profile. Additionally, along much of the core the activity is higher than expected. These are characteristics also found in the ^{36}Cl measurements of core 68002/68001 [10], and likely arise because the production of ^{36}Cl as a function of depth is still not fully understood. Within a few cm of the surface we observe a slight increase in ^{36}Cl concentrations due to SCR production. Between this peak value and the surface, the concentrations are depressed. Low near-surface concentrations are also observed in core 68002; however, production rates of ^{36}Cl in the top 6 g/cm^2 have been estimated accurately from rock samples [9], meaning deviations from the profile near the top of the core are more likely to be due to surface processes, or were introduced during sampling.

The ^{26}Al activities, on-the-other-hand provide a good fit to the predicted ^{26}Al profile at depths greater than ~10 g/cm^2. Similar to what is observed in the ^{36}Cl results there is a decrease of concentrations near the top of the core that is inconsistent with the production profile of a stable regolith. The ^{26}Al results are, however, vertically offset relative to the production profile. That is, the increase of ^{26}Al in the near-surface in response to SCR production begins at a greater depth than expected. The profiles of both nuclides peak in concentrations at a depth of ~2.6 g/cm^2. Despite the low concentration surface layer the vertically offset SCR production means that the averaged ^{26}Al concentrations in the top 6 g/cm^2 are ~19% higher than expected. SCR production of ^{36}Cl is less significant than ^{26}Al, and the excess induced by the ^{36}Cl peak at 2.6 g/cm^2 is fortuitously balanced by the low concentration surface layer.

The upper 5 cm of 60014 was found to be less cohesive than the core material beneath [2], meaning mixing is suspected during sampling and transport. The anomalously low nuclide concentration in the uppermost 0 – 1.5 cm cannot be the product of mixing of surficial material, since it would have a higher concentration. In addition, the buried but preserved production profile apparent in the ^{26}Al data extends into the top 5 cm, suggesting a lack of mixing. It is not clear at this point whether the 2 – 3 cm wide void found in the top 4 cm of the core has some bearing on the low surface concentrations.

Our findings suggest an aggradation event has occurred at this site, with deposition of between 1.5 – 2.2 g/cm^2 (~1.0 – 1.5 cm) of low nuclide concentration regolith material on top of what was previously a stable surface. There are two possible end-member sources for the overlying low concentration layer which determine the timing of the deposition event. One scenario is that the current surface layer came from significant depth (>1000 g/cm^2) and the nuclide concentrations have since increased to their current values. It would take an estimated ~0.8 Myr and ~1.1 Myr for the surface samples to attain their respective ^{26}Al and ^{36}Cl concentrations, assuming they originated from a depth where the initial concentrations were essentially zero. The alternative scenario is based on the observation that the ^{26}Al concentrations in the top two samples are consistent with an average depth of 1.8 – 2.0 g/cm^2 in a stable regolith. At this depth the SCR contribution to ^{36}Cl production has considerably diminished [9] and so the results are compatible with the corresponding low ^{36}Cl measurements. Thus it is possible the surface layer originated from a depth of a few cm and was deposited very recently.

The most likely cause for the pattern of low nuclide concentration surface material overlying what appears to be a vertically displaced ^{26}Al production profile would be an impact event blanketing the site with ejecta. Alternatively, the core may have penetrated the overturned rim of a small impact crater. This event must have happened within the last ~1.1 Myr if it were a large event that excavated material from great depth. Alternatively, it must have occurred more recently if it was a small event that exhumed regolith from only a few cm below the surface. Curiously, the sampling location was noted for an absence of small craters, whilst no compositional or layer boundaries were found by examination of the core until a depth of ~44 cm [4,5]; though the I_s/FeO measurements made in the top ~2.5 cm show less scatter than in the rest of the core, perhaps indicating this material is well mixed [4]. Our chemical analyses indicate that the chemical compositions are relatively constant for the entire depth of the core. The results of ^{41}Ca ($t_{1/2}$=0.104 Myr) and ^{10}Be measurements on our samples are pending and will help clarify our findings.

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Figure 1A and 1B show ^{26}Al and ^{36}Cl results from 60014/60013. Solid lines show production profiles.