FIFTY YEARS OF COSMOGENIC NUCLIDE STUDIES IN LUNAR SAMPLES: WHAT WE HAVE LEARNED AND WHAT WE WOULD LIKE TO KNOW.

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Introduction: The Moon has virtually no atmosphere and a relatively weak magnetic field, so in addition to galactic cosmic ray (GCR) irradiation and meteorite bombardment, the lunar surface is subjected to solar wind implantation, solar cosmic ray (SCR) irradiation, and micrometeorite bombardment. When the surface of the Moon is bombarded by cosmic rays, a wide range of radioactive and stable nuclides is produced by nuclear interactions. Immediately upon return from the Moon, and receipt at the Lunar Receiving Laboratory, cosmogenic radionuclides were measured by various investigators. Some of the highlights of these measurements are itemized below.

SCR: SCRs have lower energy but a much higher flux compared to GCRs, SCR-produced cosmogenic nuclides dominant the inventory in the upper few g/cm^2 of a surface [1]. In meteorites it is rare to find SCR-produced nuclides; surface ablation during atmospheric entry removes the upper few cm of material. On the other hand, SCR-produced nuclides are observed in nearly all lunar surface materials and the abundance of the SCR-produced nuclides provides key information to the evolutional histories of lunar surface materials, such as erosion of rock and regolith gardening. Detailed measurements of depth profiles of SCR-produced nuclides in lunar rocks provide a ground-truth archive of past solar activities. The difficulty of the measurements and the lack of ideal samples resulted in only several rock samples being studied extensively. Recently, we measured cosmogenic nuclides in the glass-coated ilmenite basalt 12054, a sample that was studied as part of a consortium [2] in 1977! Based on preliminary results, 12054 has complex exposure history and is not a good rock sample for SCR studies.

Erosion Rate: The surfaces of lunar rocks are continuously bombarded by micrometeorites, which erode the surface. This erosion can be obtained by measuring of SCR-produced ^{53}Mn and ^{26}Al depth profiles, as well as by measurements of the track density or micrometeorite impact pits. We obtained an erosion rate from ~0.5 mm/Myr for the glass coated basalt 64455 [3] to 3 - 4 mm/Myr for the breccia 68815 [4]. These represent the only direct measurements of erosion rates of a planetary surface outside of Earth.

Regolith Gardening: Lunar regolith gardening is caused by overturning of regolith materials caused by impact crater formation. This gardening process affects the maturity of the regolith – by bringing to the surface relatively immature regolith - and also excavates rocks and boulders from deeper in the regolith. Continuous impacts by meteorites and micrometeorites are considered to be the dominant cause of mixing processes on the lunar surface [5]. Twenty-one single or double drive tubes and 3 deep drill cores were collected by six Apollo missions. We have measured cosmogenic radionuclides in 16 out of the 24 cores. Gault et al. [6] estimated a turnover rate of 10^7 yr for 1 cm and 10^9 yr for 10 cm based on meteorite influx rate and laboratory impact experiment. Arnold [7] calculated a gardening rate of 10^6 yr for 1 cm and 4 x 10^7 yr for 10 cm using a Monte Carlo model. Recently, Speyerer et al. [8] predicted a regolith overturn rate of 8.1 x 10^4 yr for 2 cm and 1.0 x 10^7 yr for 20 cm using the contemporary production rate of small craters with Lunar Reconnaissance Orbiter Camera (LROC) temporal imaging. These rates, based on LROC imaging, are considerably faster than the earlier estimates. Cosmogenic SCR-produced ^{26}Al and ^{53}Mn, on the other hand, indicate turnover rates of ~2 cm/Myr for small craters over the last several million years [e.g., 9, 10]. These direct measurements by cosmogenic nuclides have provided the ground truth for lunar regolith formation and mixing models.

Pebbles vs. Bulk Soils: The work done to date on lunar pebbles and soils have noted several outstanding, and surprising features [e.g., 11, 12]: (1) most pebbles have a different depositional history than the bulk soil; (2) most pebbles contain lower cosmogenic radionuclide concentrations or lower neutron fluences than bulk soils located at the same depth; and (3) basaltic or crystalline type pebbles show these differences in exposure history, but soil breccia type pebbles do not show clear difference from bulk soils. We are investigating this unsolved problem of lunar surface processing.

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