The geochemical diversity of the lunar highlands as revealed by Lunar Prospector gamma-ray and neutron datasets.

P. N. Peplowski[1*], D. J. Lawrence[1], and J. T. Wilson[1]. [1]Johns Hopkins Applied Physics Laboratory, 11000 Johns Hopkins Road, Laurel MD 20723

Introduction: The Moon's oldest and largest geochemical terrane, the feldspathic highlands terrane (FHT), is thought to be the remnants of the Moon's primordial crust. The elemental composition of the FHT provides important constraints on the early evolution of the Moon. The composition of the FHT has conspired to limit our ability to obtain high-precision measurements, as the low concentrations of the most easily measured elements (Fe, Ti, K, Th) result in large statistical uncertainties for element-specific measurements like x-ray and gamma-ray spectroscopy. Neutron [1] and spectral reflectance data [2,3], along with analyses of meteorites inferred to have originated in the FHT [4] are revealing plagioclase-dominated regions that offer the best locations to explore the early evolution of the Moon and the nature of the primordial crust.

Recent analyses of Lunar Prospector (LP) thermal neutron measurements have revealed significant compositional variability within the FHT [1], most notably, distinct regions associated with large impact basins whose properties are consistent with high concentrations (>84 wt%) of plagioclase (Figure 1). These regions likely represent large-scale (>45-km diameter) exposures of material formed during the solidification of the Moon's global magma ocean. The thermal neutron map serves as a guide toward regions that should be studied in using element-specific measurements, such as those provided by the LP Gamma-Ray Spectrometer (GRS), to derive precision measurements of major-element (O, Mg, Si, Al, Ca, Ti, Fe) concentrations within selected highlands regions.

Solar Proton Events: Traditional analyses of LP/GRS datasets use measurements of gamma-ray emissions resulting from Galactic-Cosmic-Ray (GCR)-induced gamma-ray production at the surface, and measurements of gamma-rays from natural radioactivity. Those measurements are primarily sensitive to Fe, Ti, K, Th, and U [e.g. 5]. These are not the elements of interest for geochemical studies of the FHT, which is composed primarily of O, Si, Al, and Ca.

There exists a subset of LP-GRS data – the Moderate Proton Events, or MPEs – that likely contain new composition information of the Moon, but have not yet been studied for this purpose. During non-quiescent solar conditions, the sun can eject high-energy (up to 100's of MeV) protons into space. Often, this solar proton flux is sufficiently high that its energy deposition within gamma-ray sensors "blinds" the detectors. For these large solar particle events, the data collected are not usable for composition analysis. However, [6] noted that for the MPEs, the flux is small enough such that the sensor is not blinded, but rather sees an enhancement of gamma-ray lines not present during quiescent periods. Studying MPE-induced gamma-ray emissions represents a new application of gamma-ray spectroscopy that offers increased sensitivity to O, Mg, Si, Al, Ca, and Fe, each of which is vital to characterizing FHT composition. We present an initial analysis of MPE data acquired during passes over the lunar highlands, including just west of the Orientale impact basin (Figure 2), a region known to contain deposits of nearly-pure anorthosite (PAN),

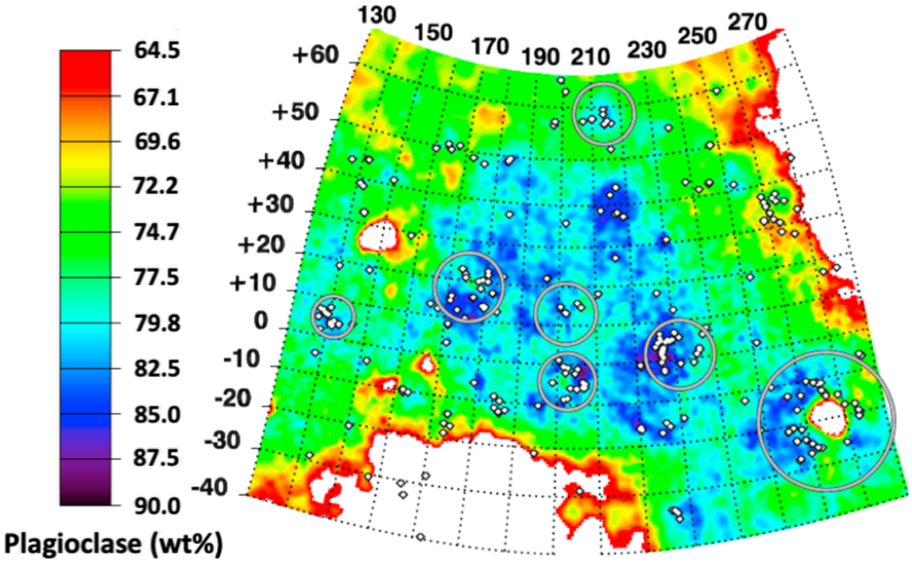

Figure 1. Plagioclase distribution in the lunar highlands, as derived from Lunar Prospector Neutron Spectrometer Measurements [1]. locations of nearly pure anorthosite (PAN) as identified with Kaguya [3] or M^3 [2] data shown as white diamonds. Large basins that appear to be associated with PAN are shown as grey outlines; (right to left) Orientale, Hertzsprung, Birkoff, Korolev, Dirichlet-Jackson, Freundlich-Sharonov, and Mendeleev.

plagioclase rocks identified from orbit by Kaguya and M3 [2,3].

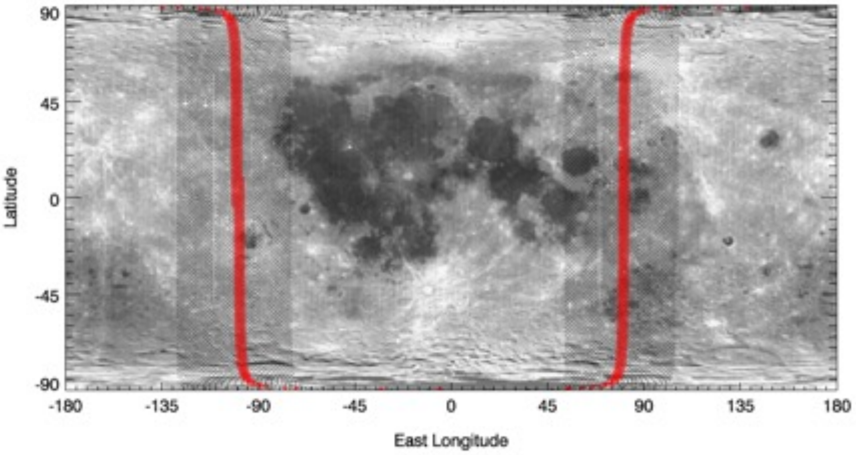

Figure 2. Ground track location of MPE shown in Figures 23. Red tracks show location of MPE and shaded region shows the background period before and after the MPE. This MPE was optimally located to measure the plagioclase-rich areas just west of Orientale basin around 90ºW and 20ºS.

Data Analysis: We have explored the link between MPE-emissions and element composition via a preliminary model of MPE-induced gamma-ray production in the lunar surface, using the radiation transport code MCNPX. MCNPX has a long history of application to planetary gamma-ray spectroscopy, having been apply to datasets from the Moon, Mars, Mercury, and various asteroids (e.g. [5]). For this initial study, we did not attempt to match the input proton spectral shape for the MPE, but employed a general exponential power law spectral shape we have used for studies of solar energetic particles [*7*]. Despite the fact that we used a generic MPE proton spectrum as input to the model, our modeled MPE spectra (Figure 3) resemble the measured MPE spectrum, both in general shape and in many identified peaks. This includes peaks resulting from O, Ca, Mg, Al, and Fe; important elements for understanding the detailed chemistry of plagioclase-rich rocks.

Future work: We will refine the MPE input spectrum, using measurements from space weather monitoring spacecraft such as ACE. Once an accurate MPE spectrum is established, we will re-run the models using compositions of varying plagioclase-to-pyroxene mixtures, including varying Mg, Fe, Ca, and Al. Those results will be used to report the element concentrations as measured along the track sampled by the MPE data (Figure 2). The results will provide constraints magma ocean models, as well as highlight locations to sample on future human or robotic missions.

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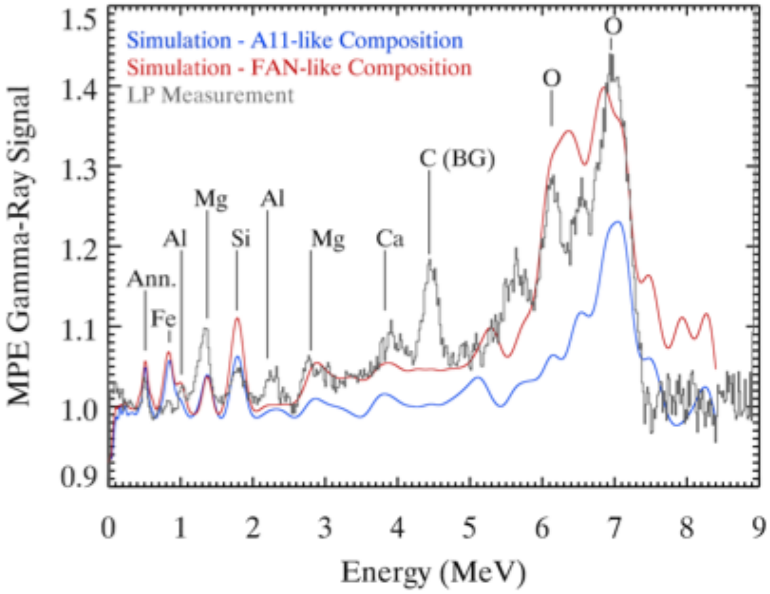

Figure 3. Simulated MPE-induced gamma-ray production for an Apollo 11 (A11) and ferroan anorthositic (highlands-like; FAN) composition, compared to the signal observed during MPE #11. Element specific peaks are labeled, and include "Ann." – electron/positron annihilation, and the 4438-keV C peak, which results from MPE-excitation of the GRS and is therefore a spacecraft background (BG).