REMOTE ANALYSIS OF LUNAR PYROCLASTIC GLASS DEPOSITS BY LRO DIVINER.

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Introduction: Telescope observations and orbital images of the Moon reveal at least 75 deposits, often tens to hundreds of km across, that mantle mare or highland surfaces [1]. These deposits are interpreted as the products of pyroclastic eruptions and designated herein as lunar pyroclastic deposits (LPD). They are understood to be composed primarily of sub-millimeter beads of basaltic composition, ranging from glassy to partially-crystallized [2]. Delano [3] documented 25 distinct pyroclastic bead compositions in lunar soil samples, though the source deposits for most of these beads have not been identified.

The pyroclastic deposits are important for many reasons. Petrology experiments and modeling have demonstrated that the pyroclastic glasses are the deepest-sourced and most primitive basalts on the Moon [4]. Recent analyses have documented the presence of water in these glasses, demonstrating that the lunar interior is considerably more volatile-rich than previously understood [5]. Experiments have shown that the iron-rich pyroclastic glasses release the highest percentage of oxygen of any Apollo soils, making these deposits promising lunar resources [6].

Taurus Littrow: The Taurus Littrow LPD, located in eastern Mare Serenitatis near the Apollo 17 landing site, is both well characterized from orbital data and represented in the lunar sample collection. The deposit covers an area of several thousand km^2 and is approximately ten meters thick [7]. The LPD extends across the Apollo 17 landing site, and the Shorty Crater orange and black glass beads, with an average diameter of 44 μm [7], are understood to be samples of this deposit. Apollo 17 orange and black glasses are identical in major elemental composition, with the color indicating the degree of ilmenite and olivine crystallization following eruption [8].

Diviner Measurements: The Diviner Lunar Radiometer Experiment on the Lunar Reconnaissance Orbiter [9] includes three thermal infrared channels spanning the wavelength ranges 7.55-8.05 μm, 8.10-8.40 μm, and 8.38-8.68 μm. These "8 μm" bands were specifically selected to measure the emissivity maximum known as the "Christiansen feature" [10]. The wavelength location of this feature, referred to herein as CF, is particularly sensitive to silicate minerals including plagioclase, pyroxene, and olivine – the major crystalline components of lunar rocks and soils. The general trend is that CF positions at shorter wavelengths are correlated with higher silica content and CF positions at longer wavelengths are correlated with lower silica content.

The Diviner spectrometer maps the entire Moon in repeated monthly cycles, and numerous data swaths cover the Taurus Littrow LPD (Fig. 1). These data have been calibrated and corrected for latitude effects. Data blocks covering 2 x 2 km areas on the surface, taken near lunar mid-day, were averaged. The maximum of these average values for the LPD is 8.41 μm, with a standard deviation of 0.06 μm.

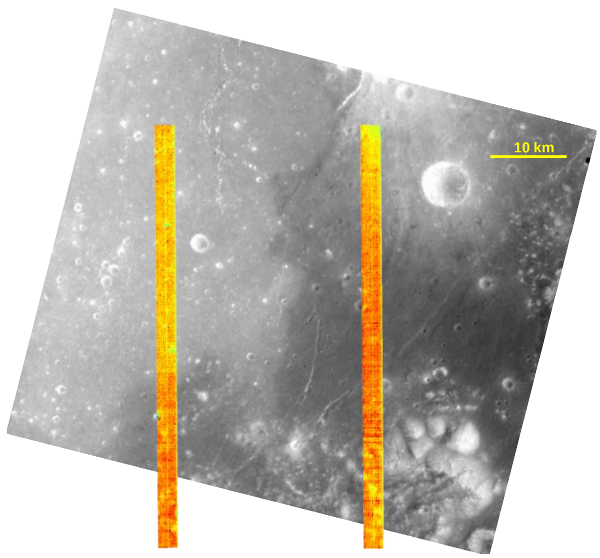

Figure 1. Diviner CF data swaths (cycle 10) over Apollo 15 metric mapping camera (frame 972) image of the dark Taurus Littrow LPD and adjacent lighter mare. Diviner data colors correspond to CF values from approximately 8.3 (yellow) to 8.4 (red).

Laboratory Spectra: Laboratory reflectance spectra of five Apollo 17 black glass samples were obtained under ambient conditions using the FT-IR spectrometer in the Keck/NASA Reflectance Experiment Laboratory (RELAB) at Brown University. Each sample was a <1 mm split from 74002, the top section of a drive tube taken on the rim of Shorty Crater [8]. The reflectance minima locations – equivalent to the CF values for these samples – range from 8.63 to 8.66 μm.

These laboratory spectra are not directly comparable to orbital data. Diviner measures emissivity under vacuum conditions, which create a thermal gradient in the uppermost microns of the surface. Measurements in a simulated lunar environment showed a shift in the CF of forsterite to shorter wavelengths by 0.13 μm with respect to measurements made under ambient conditions [11].

A discrepancy of approximately 0.1 μm remains between the orbital and laboratory CF values. This can be ascribed to limited mixing of highland and mare soil components into the pyroclastic glass deposit. Mare soil has a characteristic CF value of approximately 8.3 μm, while highland soil values range around 8.15 μm [10]. The spectral signatures of both mare material excavated from beneath the LPD by local craters, as well as highland material from distant impacts, are documented in the Apollo 17 soils [12].

Correlation of CF with FeO: As noted above, CF values are negatively correlated with silica abundance across the range of compositions and mineralogies found in lunar rocks and soils. Conversely, CF values are expected to be positively correlated to the abundance of iron over this same range of samples.

Corrected Diviner CF values were derived for 2 x 2 km areas centered on each Apollo landing site, as well as the Taurus Littrow LPD. These values were plotted against published FeO abundances for the 20 to 45 μm sieve fraction of a characteristic Apollo soil sample from each site [13,14], along with the FeO content of Apollo 17 orange glass [3]. These CF and FeO values proved to be closely correlated across the full range of Apollo soil compositions (Fig. 2).

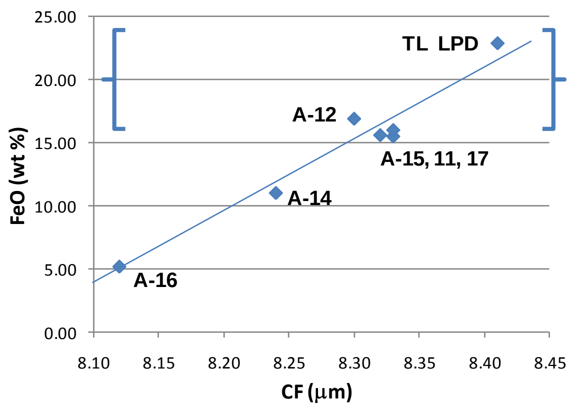

Figure 2. Correlation of Diviner CF values with sample FeO concentrations for the six Apollo sites plus the Taurus Littrow LPD. Brackets denote the range of pyroclastic glass bead compositions [3].
Regression line: FeO = 58.6 x CF – 471.0 $r^2 = 0.95$

This correlation provides the opportunity to estimate the major element composition of other LPD's. These estimates can be compared to the known compositions of pyroclastic glass beads in lunar soils.

Sulpicius Gallus: The Sulpicius Gallus LPD, spanning the mare-highland boundary on the western edge of Mare Serenitatis, contains local concentrations of red and orange material thought to be pyroclastic glass. The Sulpicius Gallus LPD has a higher albedo than the Taurus Littrow LPD, suggesting differing average compositions or differing degrees of crystallization [15,12].

Diviner data, averaged over 2 x 2 km areas on the Sulpicius Gallus LPD, consistently yields maximum CF values of 8.37 μm, with standard deviations of 0.03 μm. This CF value is lower than the value of 8.41 μm that characterizes the Taurus Littrow deposit.

Inserting a CF value of 8.37 μm into the correlation formula shown in Fig. 2 yields a FeO abundance of 19.5 wt %. This value is significantly below the FeO abundances of orange and black glasses found in the Apollo 11, 14, 15 and 17 soils, but well within the range of the very low titanium and green glasses in soils from the Apollo 14, 15, and 17 sites [3]. These data indicate that the albedo difference between the Sulpicius Gallus and Taurus Littrow LPD's is due to differing average compositions, rather than to differing degrees of crystallization.

Implications: This initial work demonstrates that:

- Diviner CF values for the Taurus Littrow LPD are closely correlated with CF values from laboratory measurements of Apollo 17 black glass.
- Diviner CF values are closely correlated with FeO abundance across the full range of Apollo soils and pyroclastic glasses.
- Diviner CF values have the potential to provide remote analyses of previously unsampled lunar pyroclastic deposits.

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