

**DERIVATION OF FEO ABUNDANCES IN LUNAR PYROCLASTIC DEPOSITS USING LRO DIVINER.**

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**Introduction:** Telescopic observations and orbital images of the Moon reveal at least 75 lunar pyroclastic deposits (LPDs), interpreted as the products of explosive volcanic eruptions [1]. The deposits 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, with a range of FeO abundances from 16.5 - 24.7 wt%. Green glasses generally have lower FeO abundances and red, yellow, and orange glasses generally have higher FeO abundances. The current study employs data from the Diviner Lunar Radiometer Experiment onboard the Lunar Reconnaissance Orbiter (LRO) to derive the FeO compositions of glasses from unsampled lunar pyroclastic deposits.

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, covers an area of several thousand km<sup>2</sup> and is estimated to be 10 m 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. The 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:** Diviner is a near- and thermal-infrared (IR) mapping radiometer with nine 21-element arrays of uncooled thermopile detectors [9]. The instrument operates mainly in a pushbroom mapping mode, with a 320 m (in track) by 160 m (cross track) detector field of view at the nominal mapping altitude of 50 km. Diviner includes three thermal IR 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 (CF) [10]. The wavelength location of this feature is particularly sensitive to silica polymerization in minerals including plagioclase, pyroxene, and olivine – the major crystalline components of lunar rocks and soils. Given the range of lunar mineralogy, a direct correlation between CF position and FeO content is expected (*i.e.* a higher CF value indicates a higher FeO content and vice versa).

**Laboratory Spectra:** Laboratory thermal IR reflectance spectra of 15 Apollo soil samples, characterized by the Lunar Soil Characterization Consortium [11,12], were measured under ambient conditions using the FT-IR spectrometer in the Keck/NASA Reflectance Experiment Laboratory (RELAB) at Brown University [13]. Samples are the 20 - 45 µm sieve fractions of bulk soils. In addition, the spectra of two samples rich in pyroclastic glass were measured. Sample 74002 consists of nearly pure black glass beads from the Taurus Littrow LPD. Sample 15401 contains a large proportion of Apollo 15 green glass beads. The wavelength of the reflectance minimum in the 8 µm region of each RELAB spectrum is equivalent to the emissivity maximum, or CF. These values proved to be closely correlated with FeO concentrations for the 20 – 45 µm splits of the soils [11, 12] and glasses [3], with an R<sup>2</sup> value of 0.9.

This correlation between CF and FeO extends across the full compositional range of sampled lunar soils, from FeO concentrations of 4.62 wt.% (soil 61221) to 22.9 wt.% (pyroclastic glass 74002). These results provide a model for investigating the correlation between lunar soil FeO abundances and CF values derived from Diviner multispectral measurements.

**Correlation of Diviner CF with FeO:** Diviner CF values, reduced using the most recent corrections of Greenhagen *et al.* [14], were derived for 2 x 2 km areas centered on each Apollo landing site, as well as the Taurus Littrow LPD. All data were taken near lunar mid-day to minimize shadowing effects. These values were plotted against published FeO abundances for the 20 - 45 µm sieve fraction of a characteristic Apollo soil sample from each site [11,12], along with the FeO content of Apollo 17 pyroclastic glass [3]. The CF and FeO values proved to be closely correlated across the full range of Apollo soil compositions (Fig. 1). This

close correlation provides the basis for estimating the FeO concentration of other LPDs.

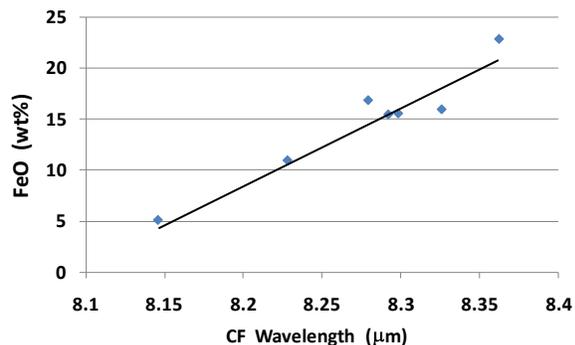


Figure 1. Correlation of Diviner CF values with sample FeO concentrations for the six Apollo sites plus the Taurus Littrow LPD. Regression line formula:  $\text{FeO} = 74.39 \times \text{CF} - 600.9$   $R^2 = 0.9$

**Rima Fresnel:** This LPD is centered on a set of sub-parallel fissures, and covers more than 2,120 km<sup>2</sup> [15]. It is the closest LPD to the Apollo 15 landing site. Blewett and Hawke [15] used maps based on Clementine multispectral data to estimate an FeO content of 15.1 +/- 0.4 wt.%. This FeO abundance is close to that of typical Apollo 15 soils, as well as to that of Apollo 15 green glass.

The mean Diviner CF value for a 2 x 2 km area centered near 28° 26' N, 3° 59' E, one of the darkest areas of the deposit, is 8.29  $\mu\text{m}$  ( $\sigma = 0.04 \mu\text{m}$ ). Inserting these values into the formula shown in Fig. 1 yields an **FeO concentration of 15.8 +/- 2.2 wt.%**.

**Aristarchus:** This extensive pyroclastic deposit covers most of the 170 x 200 km Aristarchus plateau, located in central Oceanus Procellarum. The deposit displays a range of pyroclastic glass concentrations and spectral signatures, ascribed to mixing with underlying material induced by cratering [16,17]. Wilcox *et al.* [18], using radiative transfer modeling, estimated an FeO concentration for the Aristarchus pyroclastic deposit of 20.75 wt.%.

Diviner data were averaged over a 2 x 2 km area centered near 26° 51' N, 52° 22' W. This area is one of the darkest on the Aristarchus plateau, and therefore is understood to represent one of the least-contaminated deposits of pyroclastic glass. The mean CF value is 8.34  $\mu\text{m}$  ( $\sigma = 0.03 \mu\text{m}$ ), implying an **FeO concentration of 19.5 +/- 2.2 wt.%**.

**Sulpicius Gallus:** The Sulpicius Gallus LPD, on the western edge of Mare Serenitatis, contains local concentrations of highland material, as well as red and

orange material thought to be pyroclastic glass [8]. Wilcox *et al.* [18] estimated that the Sulpicius Gallus LPD contains 17.25 wt.% FeO.

Diviner data were averaged over a 2 x 2 km area centered near 29° 9' N, 10° 17' E in one of the darkest regions of the Sulpicius Gallus LPD. The mean CF value is 8.37  $\mu\text{m}$ , ( $\sigma = 0.04 \mu\text{m}$ ). These values yield an **FeO concentration of 21.7 +/- 3.0 wt.%**.

**Discussion:** This work demonstrates that laboratory CF values are closely correlated with FeO abundances across the full compositional range of soils and pyroclastic glasses in the Apollo sample collection ( $R^2 = 0.9$ ). Diviner CF values for the Apollo landing sites and the Taurus Littrow LPD are also closely correlated with sample FeO abundances ( $R^2 = 0.9$ ).

Diviner-derived FeO abundances for three unsampled LPDs are within the compositional range of Apollo glass beads. The Diviner FeO value for the Rima Fresnel LPD is nearly identical to the FeO abundance derived from Clementine multispectral data. Diviner results for the Aristarchus LPD match an independent estimate from radiative transfer modeling, within one standard deviation. The FeO estimates from Diviner data and radiative transfer modeling for the Sulpicius Gallus LPD, however, are statistically different. This deposit crosses both mare and highland surfaces, and the discrepancy may reflect differing degrees of contamination with highland material. Diviner CF values have the potential to provide remote analyses of FeO concentrations in many other unsampled lunar pyroclastic deposits.

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