Introduction: Lunar deposits of pyroclastic material, referred to as dark mantle deposits (DMDs), are fine-grained, low-albedo volcanic materials [1]. Previous studies identified over 100 DMDs across the lunar surface, ranging from ~10-50,000 km² [2,3]. The largest of these are known as “regional” DMDs, while the smaller are “localized” DMDs [4]. DMDs are believed to represent the eruption of gas-rich magmas which originated from mafic parent melts sourced from primitive, unaltered mafic magmas [5]. Regional DMDs were found to contain iron- and titanium-rich glass, and mafic devitrified beads [4,6,7]. Iron-rich volcanic glass has also been identified in localized DMDs [8,9]. Volcanic glasses are important in characterizing the lunar interior and understanding the origin and evolution of basaltic magmatism on the Moon. Understanding the mineralogical diversity and variations in crystallinity in localized DMDs can aid in identifying the sources and eruption mechanics of these deposits.

Three localized DMDs were analyzed using data from the Moon Mineralogy Mapper (M3) [10] to (a) document DMD mineralogy, (b) characterize the mineralogical variation within and between deposits, and (c) compare the mineralogy of DMDs to nearby mare basalts, in an attempt to constrain mineralogical diversity in localized DMDs.

Data and Targets: Spectral analyses of the localized DMDs are based on observations from M3, a visible and near-infrared spectrometer covering the spectral range 0.4-3 μm at a spatial resolution of ~140-280 m/pixel [10–12]. A continuum-removal was applied to the spectra, approximated by a straight line fit between 0.73-1.62 μm and 1.62-2.58 μm for the 1 and 2 μm bands, respectively [8]. Mosaics of context images from the Kaguya (SELENE) Terrain Camera (TC) support the spectroscopic products analyzed here [13].

The localized DMDs occur in floor-fractured craters, including Alphonsus, J. Herschel, and Oppenheimer crater. Each localized DMD is located near a mare unit. Spectral analyses from the DMDs in Alphonsus, J. Herschel, and Oppenheimer craters are compared to spectra of the DMDs in Lavoisier and Walther A craters [8,14].

Results: Alphonsus DMD. Spectra were extracted from the three largest sub-deposits in the Alphonsus DMD (Fig. 1). There are variations in albedo within each sub-deposit (inset, Fig. 1A). Spectra of the sub-deposits were taken at various distances from the vent to examine this variation. Unit names (Light, Intermediate, etc.) indicate changes in albedo across the DMD.

Spectra taken close to the vent show 1 μm bands shifted to longer wavelengths and deeper absorption depths (Fig. 1). This suggests that inside the vent and in proximity (Dark unit), spectra are dominated by mafic pyroclastic materials. As distance from the vent increases, spectra become contaminated by noritic crater floor material. This variation is interpreted to represent variable thickness of the deposit. DMD thinning also agrees with the albedo variation.

Spectra were also taken in Mare Nubium (Fig. 1D). The maria show a slightly shorter 1 μm band position,
a slightly longer 2 μm band position, and a narrower, symmetric band shape relative to the DMDs. This distinction in spectra signifies a variation in mineralogy or internal structure (crystallinity) between the two units. Previous analyses [15] interpreted the wide, asymmetric 1 μm absorption in DMDs such as Alphonsus to indicate olivine. However, olivine does not have a 2 μm absorption feature, and the inclusion of olivine or other mafic minerals would not explain the band center shift to shorter wavelengths at 2 μm. We conclude this spectral signature is indicative of amorphous materials in the form of iron-enriched volcanic glass (e.g., [8]).

**J. Herschel and Oppenheimer DMD.** The J. Herschel DMD spectra show similar features to Alphonsus: the shape and location of the 1 and 2 μm bands are distinct from the crater floor and nearby maria, and are consistent with mafic materials containing glass (Fig. 2).

Two of the smallest DMD sub-deposits in Oppenheimer crater (N, SSE) show a similar variation in albedo with distance as in the Alphonsus DMD, which indicates spectral variation and thinning of the deposit. The DMD spectra appear distinct from the surrounding mare deposit, with a similar shift in the 1 and 2 μm bands to longer and shorter wavelengths, respectively, as in Alphonsus and J. Herschel DMDs. This indicates volcanic glass in the Oppenheimer DMDs, although the relative strength of the 1 and 2 μm bands is different than that in the Alphonsus and J. Herschel glassy spectra. In addition, two new DMDs were identified to the northeast of Oppenheimer, in Dryden S and T craters. These DMDs are spectrally similar to the Oppenheimer DMDs.

**Discussion:** Assuming the spectral signatures in the DMDs represent the presence of volcanic glass, it is possible to distinguish between glass compositions using a combination of the 1 and 2 μm band positions and 2 μm to 1 μm band depth ratios (not shown here). Based on these two metrics, the spectral signatures of the Alphonsus and J. Herschel DMDs are similar to the green glass returned from the Apollo 15 landing site [16], while the Oppenheimer spectra resemble orange glass returned from the Apollo 17 landing site [7]. These variations may indicate the presence of olivine (in the case of Alphonsus and J. Herschel DMDs) and/or ilmenite (Oppenheimer DMD).

In addition to a thinning of the DMD, the variation in spectral signatures across the isolated sub-deposits may indicate a variable amount of volcanic glass in the DMDs, with a higher concentration of glass closer to the central vent. This may be evidence of a sporadic, potentially repetitive explosive emplacement style typical of vulcanian eruptions on Earth. In larger, more continuous Hawaiian eruptions, temperatures and optical densities increase towards the center of the eruptive plume, leading to more crystalline material closer to the eruptive vent [16]. However, vulcanian eruptions are smaller and sporadic, with eruptive optical densities and temperatures low enough to rapidly quench erupting magma, creating glass [17]. Assuming this formation mechanism is representative of most localized DMDs, volcanic glass may be detectable in other similar deposits on the Moon.


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**Figure 2.** (A) Continuum-removed spectra of the DMDs, including Walther A and Lavoisier DMDs [11, 16], and Mare Frigoris (near J. Herschel). (B) Continuum-removed spectra of the glassy DMDs, relative to lunar pyroclastic orange glass and green glass. Spectra are offset for clarity.