FORMATION OF THE SPINEL-RICH SINUS AESTUUM DARK MANTLE DEPOSITS. C. Sikes[1], J. M. Sunshine[1,2], and M. Newcombe[1], [1]University of Maryland, Department of Geology, College Park, MD, 20742 (cvarahsi@umd.edu), [2]University of Maryland, Department of Astronomy, College Park, MD, 20742

Introduction: The Sinus Aestuum Dark Mantle Deposit (DMD) is located on the central nearside of the lunar surface and in the heart of the Procellarum KREEP Terrane (PKT, [1]). Sunshine et al. [2] first reported unique 2 µm spectral signatures in this region using data from the Moon Mineralogy Mapper (M^3), which were interpreted as an anomalously high abundance of spinel [2]. Unlike other remotely detected lunar spinels [3], Sinus Aestuum spinels exhibit a remarkably lower albedo as well as a unique spectral feature at visible wavelengths [4].

DMDs: DMDs are associated with high concentrations of picritic glass beads, thought to be deposited during lunar fire fountain eruptions. Association of the SA spinel deposits with the SA DMD suggests a common origin and emplacement [4]. While this supports a pyroclastic origin of the spinels, their unique formation mechanism, and possible relation to the PKT, is still poorly understood. Further remote sensing analyses, combined with laboratory melting experiments, will help better understand the composition and formation mechanism of these unique DMD spinels and their implications for early lunar volcanism.

Data and Methods: The primary data used in this study is from M^3, an imaging spectrometer onboard Chandrayaan-1 with 140 m/pixel spatial resolution [5]. M^3 covers a spectral range of 0.43 to 3 µm with 20 to 40 nm spectral sampling over 85 spectral bands [5]. In this analysis, M^3 data are first smoothed spectrally using a three band resistant mean. A continuum slope is then removed from each spectrum in the scene.

Mapping: The DMDs are identified using 1 and 2 µm integrated band depth (IBD), band center maps, and abundance maps from spectral mixing analysis. The characteristics of spinel—a strong 2 µm band and a weak 1 µm band—are mapped as the ratio of IBD-2 and IBD-1 [6]. The band center maps are found by calculating the wavelengths of the minima of both the 1 µm and 2 µm bands; spatial changes in band center reflect changes in mineralogy [7]. Spectral mixture analysis [8] is used to model spectra as a linear combinations of key compositional endmembers (e.g., mare, highland, DMDs) and to produce abundance maps for each endmember.

Stratigraphy: Stratigraphic units in this region include Imbrium Basin ejecta which is sequentially overlain by mare volcanism, pyroclastic deposits (DMD), Eratosthenes cratering/ejecta, and Copernicus cratering/ejecta [9]. While the central portion of the DMD is buried by younger maria, DMD and spinel are exposed on the surrounding highlands and in craters and ejecta that have subsequently impacted the flooded regions. Analysis of crater walls and ejecta deposits therefore provides important constraints on the horizontal and vertical distribution of the Sinus Aestuum DMD.

Spinel-rich DMD in Mare: Gambart craters B and G are in the central, mare flooded section of Sinus Aestuum. Sunshine et al, [10] detected the presence of spinel within the crater walls and ejecta using IBD maps, supporting the presence of subsurface DMD and spinel deposits. Band center maps are now seen to reveal localized changes in the 1 and 2 µm centers of the ejecta from Gambart G (Figure 1a). The 2 µm band centers of the ejecta is found to fall between that of the spinel and mare. A lower-calcium pyroxene component would correspond to a coupled lowering of 1 and 2 µm band centers. However, the 2 µm shift is much greater than the 1 µm and thus is inconsistent with pyroxenes (Figure 1b) [7]. Instead, the ejecta is interpreted to represent a mixture between mare and spinel, providing new constraints on the depth and spatial extent of spinel-rich DMDs in this area.

Undiscovered deposits: The IBD maps reveals two previously undiscovered spinel deposits southwest of Gambart A (Figure 2). Small, sub-pixel, spinel deposits (<140 m^2) are observed within the crater walls and in the ejecta of two craters (400 m and 75 m diameter). The deposits were buried below the overlying mare before being excavated via impact. The presence of these deposits suggests the spinel bearing lithology extents further east, and further into the PKT terrain, than previously thought. The identification of these deposits suggests that there are likely additional undiscovered deposits below the spatial resolution of M^3.

Experimental constraints on spinel formation mechanisms: Although the exact composition of the spinels present within SA is unclear, the composition of the spinel has significant implications for formation. Spinel with compositions ranging from chromite ($FeCr_2O_4$) to ulvöspinel (Fe_2TiO_4) has been found to form on the Moon via fractional crystallization of picritic melts [11]. Al-rich spinel ($[Fe^{2+},Mg][Cr,Al]_2O_4$) may also be present, which has been proposed to form through assimilation of picritic melts with anorthitic crust [4, 11]. To explore the formation of these two families of spinel compositions, we have initiated two sets of 1 atm experiments utilizing a Deltech gas mixing furnace (Figure 3).

Crystallization experiments: Equilibrium experiments will be performed on a wide range of lunar basaltic melt compositions and conditions to help determine the ideal conditions for spinel formation (Figure 3A). Melt compositions will range from green (low-Ti) to red (high-Ti) Apollo glass compositions and temperatures will range from 1000°C to 1450°C. Oxygen fugacity will be controlled via flowing CO-CO_2 mixtures through the furnace; a range of oxidizing (~IW+2) to reducing (~IW–2) conditions will be studied.

Anorthite assimilation experiments: These experiments will be conducted in a 1-atm gas mixing furnace and a piston cylinder apparatus by placing lunar basaltic melts into anorthite capsules (Figure 3B). Melt composition and temperature will be varied as above. Previous studies have demonstrated that assimilation of anorthite into Apollo green glass (low-Ti) basaltic melt triggers the crystallization of Al-rich spinel [11]. We will explore the composition and spectral properties of spinel produced by assimilation of anorthite into a wider variety of basaltic melt compositions and conditions [11].

Analysis: Spinels produced in both manners will be analyzed via electron microprobe and spectrometer in order to determine their composition and spectral properties. Comparing the spectra of these spinels to SA may help link the two compositions and formation conditions. Finally, we note that the proximity of the Sinus Aestuum DMDs to long-lived heat sources in the PKT may play a significant role in their unique formation. The presence of Th may promote extensive anorthite assimilation and/or re-melting of crustal troctolite, both of which may promote spinel formation [11].

References: [1] Joliff et al, 2000, J.G.R, 105(2), 4197-4216. [2] Sunshine et al, 2010, LPSC 41, Abstract #1508. [3] Pieters et al, 2011, 116(6). [4] Yamamoto et al, 2013, G.R.L., 40(17), 4549-4554. [5] Green et al, 2011, J.G.R., 116(10). [6] Cloutis et al., MAPS, 2004. [7] Klima et al, 2011, 116(6) [8] Adams and Gillespie, 2006, Remote Sensing of Landscapes with Spectral Images. [9] Gaddis et al, 2014, LPSC 45, #2254 [10] Sunshine et al, 2014, LPSC 45. [11] Prissel et al, 2014, E.P.S.L., 403, 144-156.

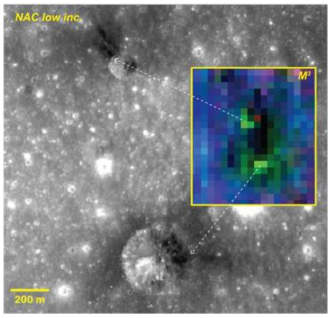

Figure 2: New spinel deposits observed 7 km west of Gambart A. Inset map of M^3 data: 1 µm IBD (red), 2 µm IBD (green), 1.6 µm albedo (blue). Spinel-rich pixels are green and have high 2 µm IBD values.

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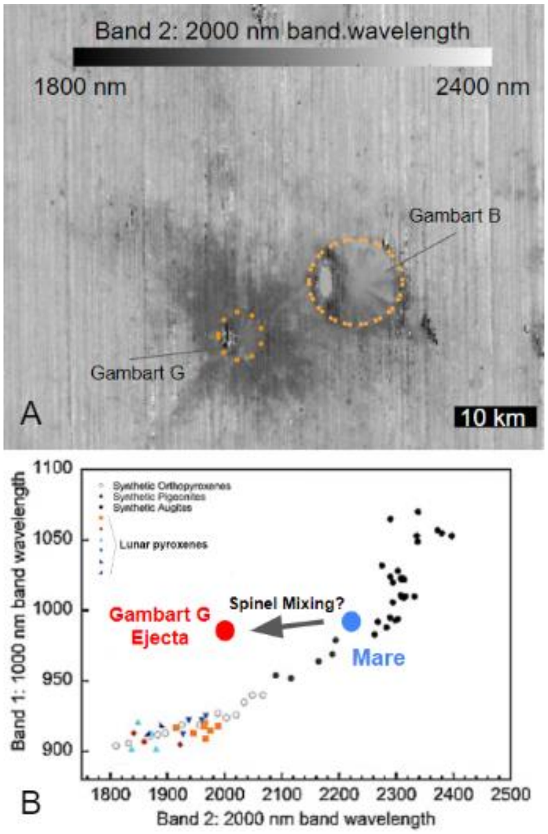

Figure 1a: 2 µm band center map showing Gambart B and G. Note the short 2 µm band center of the ejecta of Gambart G. A large shift in the 2 µm band is observed with only a minor shift of the 1 µm band. **Figure 1b:** The band centers of the ejecta (red) is plotted among synthetic and lunar pyroxenes [10]. The band centers of the ejecta are not consistent with pyroxenes, instead suggesting the ejecta is a mixture of spinel and maria.

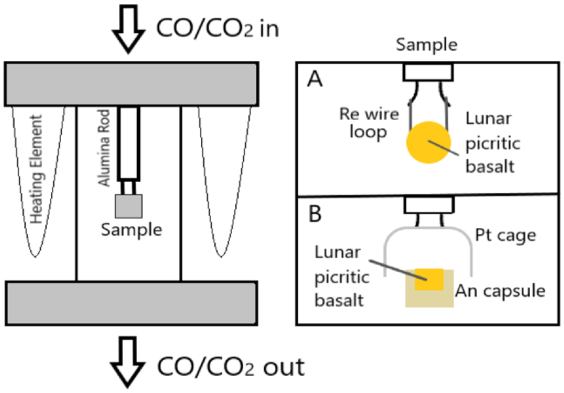

Figure 3: Deltech gas mixing furnace schematic. **Figure 3a:** Picritic melt will be suspended from Re wire and allowed to equilibrate to produce spinel. **Figure 3b:** Picritic melt will be surrounded by anorthite and equilibrated to produce Al-rich spinel.