GEOMORPHOLOGICAL AND MINERALOGICAL MAPPING OF LUNAR PYROCLASTIC DEPOSITS AT SINUS AESTUUM: INSIGHTS INTO SPINEL-BEARING MAGMAS

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Introduction: The formation of dark mantle (pyroclastic) deposits on the Moon may be associated with the major episode of volcanism in early lunar history \cite{1}. Geological and morphological mapping of these deposits can inform us on the nature of processes associated with volatile-drive magmatism and may also help to identify possible vents. Assessments of compositions of pyroclastic materials can indirectly provide information about the composition of the potential magma sources, and consequently inform us of the heterogeneity/homogeneity of the lunar mantle.

In this study we focused on large pyroclastic deposits at Sinus Aestuum. Studies of water (H\textsubscript{2}O/OH) contents at large pyroclastic deposits between latitudes $\pm$30\degree with new thermally corrected Moon Mineralogy Mapper (M\textsuperscript{3}) data suggest that Sinus Aestuum is the only large pyroclastic deposit that lacks clear spectral evidence for the presence of water sourced from the lunar interior \cite{2}. Interestingly, Sinus Aestuum is the only pyroclastic deposit that contains significant exposures of spinel \cite{3-5}. The link between water content and spinel content for Sinus Aestuum is explored here as it may be related to emplacement conditions, magmatic composition, and/or post deposition modification.

We focused on the following questions in our study. 1) Why does Sinus Aestuum lack evidence for lunar interior water as compared to other very large pyroclastic deposits? 2) Is there any connection between the absence of lunar interior water and the presence of spinel at Sinus Aestuum? 3) What does the absence of lunar interior water and presence of spinel at Sinus Aestuum tell us about magmatic source regions, pyroclastic eruptions, and/or post-depositional processes for this deposit?

Methods: We performed detailed geomorphological mapping at Sinus Aestuum using the Kaguya Multi-band Imager (MI) 750 nm reflectance data. We applied empirical band parameters and band ratios originally derived for Clementine data to the MI data to assess compositional differences among the mapped geomorphological units. Color composite mosaics were created by assigning the band ratio 950 nm/750 nm to the red channel (stretched for ratio values $\sim$1.15-1.24), 750 nm reflectance to the green channel (stretched for value $\sim$0.15-0.22), and 415nm/750nm ratio to the blue channel (stretch for values $\sim$0.6-0.7). In this composite, pyroclastic deposits appear red, highland materials appear green, and mare materials appear blue, similar to methods of \cite{6}. We performed nonlinear spectral unmixing analyses using Hapke radiative transfer modeling and in-scene endmembers on overlapping MI and M\textsuperscript{3} data to investigate lateral/vertical mixing of these units.

Spinels was mapped using radiative transfer modeling in conjunction with M\textsuperscript{3} data, and the spatial relationships between spinel and pyroclastic materials were used to assess whether its formation is associated with pyroclastic eruption. The spectral features of pixels with highest abundance of spinel (i.e., $>$ 90\%) were examined to understand spinel speciation (e.g., Cr or Al spinel), which may inform us about magma sources and formation processes.

Results and Discussion: The outlines of mapped geomorphic units at Sinus Aestuum were overlain on the band parameter and band ratio map and results are presented in Fig. 1a. Most pyroclastic deposits at Sinus Aestuum are pink in color, indicating pyroclastic materials (red) mixed with mare materials (blue). This dilution by mare materials may explain the absence of water features, but inferring composition from such simple parameters is non-unique.

The nonlinear spectral unmixing results from MI data are shown in Fig. 1b. Overall, the 3 major lithologic units (highland, mare, and pyroclastic deposits) match well with band ratio and geomorphological maps, but the former exhibit much sharper boundaries between different units, suggesting lateral mixing of materials across geologic contacts. Another major difference is that the distribution of mare component estimated with spectral unmixing is significantly greater than what is inferred from the band ratio map and the geomorphological map (Fig. 1a), which is consistent with telescopic observations by Pieters, et al. \cite{7}. Most of pyroclastic deposits are pink, light red, or light yellow in color (Fig. 1b), suggesting the presence of mare basalt (blue) and highland (green) ejecta from the Copernicus impact, which is not apparent in the band ratio and morphologic maps. If Sinus Aestuum magmas or pyroclastic deposits once had water, current abundance in the bulk materials at this location might be $\sim$10s ppm because even ‘freshly’ excavated pyroclastic materials exhibit no
The $M^3$ spectral unmixing results at Sinus Aestuum are consistent with those from MI data. Estimates of spinel were overlain on the MI 750 nm map in Fig. 1c. Only pixels with over 10% spinel are color coded to avoid ambiguity in identification. This estimation shows that much of the spinel is associated with pyroclastic deposit regions and often occurs as dark halos around small craters (Fig. 1c). This suggests that most spinel is present in the shallow subsurface, similar to results of [4], and has since been excavated by impacts (~10s m according to the crater diameter to depth scaling law and [1]).

$M^3$ spectra for pixels with different spinel contents are plotted in Fig. 1d. We observe strong concave up trends at wavelengths from ~500 nm to 900 nm and steep slopes from 800 nm to 1500 nm. The glass component is most consistent with Ti-rich black beads. There may be two absorptions in the 500 – 900 nm region, one absorption at ~500 – 650 nm and the other at ~650 – 800 nm. The strong absorption centered at 550 nm due to octahedral $Cr^{3+}$ in Cr spinel [8] coupled with octahedral Fe$^{2+}$ in aluminate spinel [9] could create strong concave up trends from 500 to 800 nm. However, this interpretation is non-unique. Other mechanisms should be explored in future studies to better understand the type(s) of spinel and glass that might be present in these regions.

Conclusions: We studied the geomorphological and mineralogical features of the pyroclastic deposit at Sinus Aestuum using the MI and $M^3$ data. Our results showed that pyroclastic materials at Sinus Aestuum are heavily contaminated by surrounding lithologies. Nonlinear spectral unmixing analyses showed that the contamination is not sufficient to explain the entire absence of water given our current understanding of detection limits (~10s ppm) in $M^3$ data. The hypothesis of a water-poor magma source at Sinus Aestuum remains plausible, but water loss via degassing cannot be ruled out. The weak absorptions centered at around 550 nm and 750 nm of relatively pure spinel spectra may be indicative of octahedral $Cr^{3+}$ in Cr spinel and octahedral Fe$^{2+}$ in aluminate spinel, respectively. The presence of octahedral Fe$^{2+}$ in aluminate spinel suggests fast cooling rates that require thin/no vapor clouds during the pyroclastic eruption [9], which would be in accordance with a dry magma source.