ORBITAL ASSESSMENT OF THE DISTRIBUTION AND COMPOSITION OF SPINEL ACROSS THE CRISIUM REGION: INSIGHTS FROM LUNA 20 SAMPLES.

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Introduction: Spinel group minerals are a minor component of lunar surface materials, but their composition and origin provide extensive insight into the thermal and geochemical evolution of the Moon. Historically, the global distribution of spinel has been poorly constrained, other than scattered identifications of an unusual, tentatively-characterized Mg-spinel-dominated lithology not readily observed in the lunar sample collection[1-3]. Over the last decade, laboratory analyses have contributed to a better understanding of the visible-near infrared spectral character of common lunar Mg,Fe,Cr-bearing spinel compositions and mixtures[4-6]. We draw upon these characterizations to develop and validate a suite of spectral parameters to detect the presence of spinels in Moon Mineralogy Mapper (M^3) data, in the context of groundtruth from Luna 20 samples. These tools provide an improved understanding of the distribution of spinels across the lunar highlands, providing important geospatial context for historical and future sample analyses.

Table 1: Definitions of spectral parameters.

Parameter	Formula
Spinel Ratio	$\frac{R1400}{R1750}$
Pyroxene Ratio	$\frac{R700 + R1200}{R950}$
Pure Anorthosite Ratio	$\frac{R1000 + R1500}{R1250}$
Slope Ratio	$\frac{1000\text{ nm slope}}{2000\text{ nm slope}}$
Spinel Parameter	$\frac{\left(\frac{R1250 - R750}{500}\right) * 1350 + R1250}{R2600}$

Methods: We use M^3 data with updated thermal, topographic, and photometric corrections[7], improving the reliability of spinel detections. Spinel exhibits a deep, broad composite spectral absorption feature across the 2000 nm region, extending beyond the M^3 wavelength range. This precludes accurate continuum removal or band depth measurements. Instead, we employ a series of parameters targeting several independent diagnostic properties of spinel spectra, described in Table 1. The Spinel Ratio and M^3 False Color Composite were previously developed[2]; the Slope Ratio and Spinel Parameter are new. Each of these parameters is subject to false positives in some cases, but agreement between all parameters strongly suggests the presence of spinel. While previous analyses focused strictly on pure (virtually Fe,Cr-free) Mg-Al spinels that lack a 1000 nm absorption[2], we consider a broader compositional range including a significant Fe,Cr component, which causes a lower albedo and a weak spectral absorption near 1000 nm[4-6].

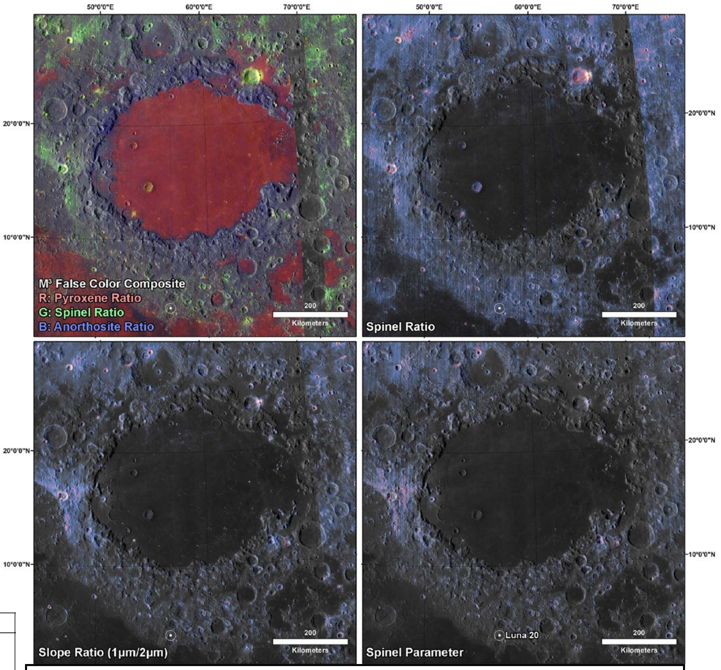

Fig. 1: M^3 spinel parameter maps for the Crisium region.

Results: M^3 parameter maps for the Crisium region are presented in Fig. 1. Spectral diversity is well-captured in the M^3 false color composite, which targets the distribution of spinel, pyroxene, and crystalline plagioclase across the region. From this map, four broad lithologic units are evident: (1) Mare basalts (red, indicating a far stronger 1000 nm feature than 2000 nm feature); (2) Norites (yellow, indicating 1000 nm and 2000 nm features with comparable strengths); (3) Pure Anorthosites (blue, indicating a lack of 1000 and 2000 nm absorptions and presence of an absorption at 1250 nm); and (4) Highlands Soils (grey-to-green, indicating a variable-strength absorption at 2000 nm with a comparably weaker 1000 nm feature). The highlands soil signature tentatively indicates the presence of minor spinel and is widespread across the exterior of Crisium, including both the Luna 20 site as well as Macrobius, which hosts the closest previous Mg-Al spinel identification to Luna 20[2]. What are the spectral characteristics of surface units bearing this signature, and are they consistent with the presence of Mg,Fe,Cr-bearing spinel?

Representative spectra capturing spectral diversity among relevant materials are presented in Fig. 2. Spectrum A (left) is a 10x10 pixel average of an optically mature highlands soil north of Macrobius. This provides a baseline for comparing other spectra of interest and serves as an appropriate featureless spectrum for deriving relative reflectance (right). Spectra B-D are 2x2

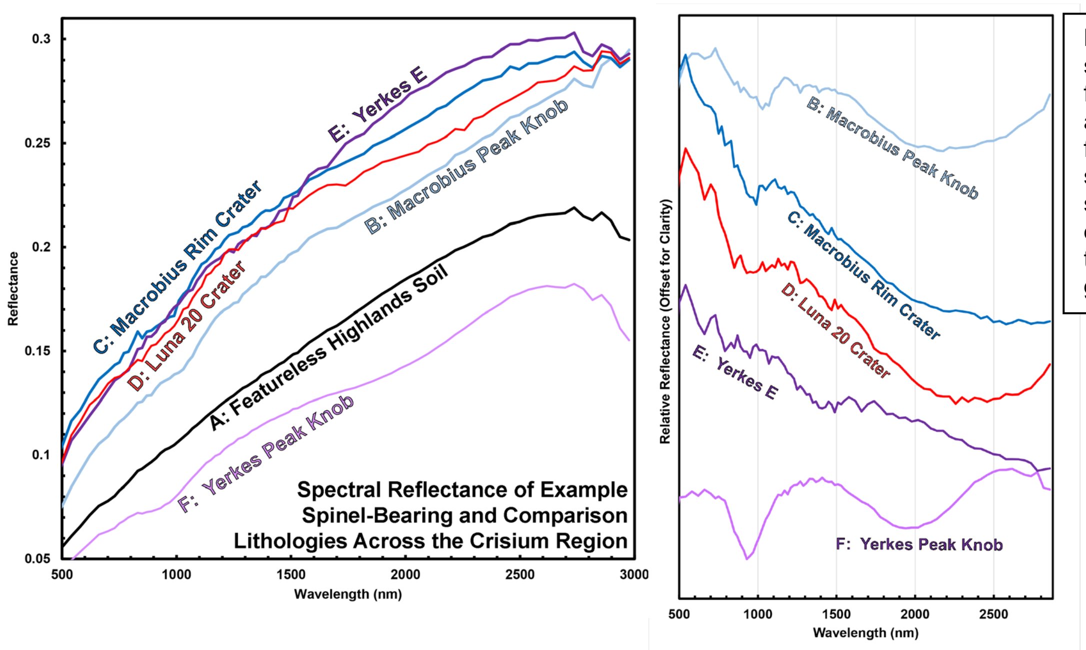

Fig. 2: Representative M^3 reflectance (left) and relative reflectance (right) spectra demonstrating spectral diversity across the Crisium region.

pixel averages extracted from candidate spinel-bearing areas. Spectra E and F are 2x2 pixel averages of comparison noritic and pure anorthositic lithologies.

The candidate spinel-bearing materials exhibit several spectral similarities consistent with the presence of spinel. Each of these exhibit a subtle but discernable concave-up shape across the 2000 nm region (left). In relative reflectance, which increases spectral contrast, this feature appears broad, deep, and extends from ~1600-3000 nm (right). The feature appears weaker in the Macrobius rim crater (C) than in the Macrobius floor knob (B) and Luna 20 crater (D).

Spectral character across the 2000 nm region is significantly different in comparison spectra. Pure anorthosites from Yerkes E (E; associated with the inner rim of Crisium) and the mature highlands soil (A) exhibit a concave-down shape across this wavelength range. Norites from Yerkes (F) exhibit an absorption feature around 2000 nm, but this feature is considerably narrower, deeper, and centered at shorter wavelengths that the feature in spectra B-D.

Candidate spinel-bearing spectra (B-D) each exhibit broad local reflectance maxima between ~1100 and ~1600 nm, The local reflectance maximum in the noritic spectrum (F) appears slightly narrower. In contrast, the mature highlands soil (A) is featureless across this range, while pure anorthosite (E) exhibits an absorption feature centered around 1250 nm consistent with the presence of crystalline plagioclase[8].

The candidate spinel-bearing spectra (B-D) exhibit weak, possibly asymmetric absorption features around 1000 nm, similar to Fe,Cr-bearing spinels measured in the laboratory [4-6]. Alternatively, the 1000 nm feature could arise from small amounts of pyroxene in association with MgAl spinel. A significantly deeper, more symmetric feature in this wavelength range is observed in the noritic spectrum (F). A 1000 nm feature is not observed in the featureless soil or pure anorthosite.

Interpretation and Conclusions: The spectral properties of B-D are consistent with the presence of small abundances of Mg,Fe,Cr-bearing spinel within a feldspathic matrix, based primarily on their deep, broad 2000 nm absorption in association with a weak 1000 nm feature. This interpretation is validated by groundtruth measurements of Luna 20 samples, which demonstrate the presence of small quantities (<5 wt%) of Mg,Fe,Cr-bearing spinel in a plagioclase-rich highlands soil, and a lack of pure MgAl spinel[9]. Similar spinel abundances in plagioclase-dominated mixtures have been shown to be readily detectible[4]. Luna 20 spinels were found to be the product of shallow crustal processes, rather than exposure from depth. This is consistent with the spectral properties and geologic associations observed in M^3 data, as spectral evidence for minor spinel is observed within optically immature highlands soils across the region, as opposed to within Crisium basin materials derived from depth. Our identification of widespread Mg,Fe,Cr-bearing spinel differs significantly from previous remote sensing analyses, which reported small, isolated outcrops of Mg-Al spinel ~100 m in scale[2].

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References: [1]Pieters *et al.*, (2011), *JGR*, 116, [2]Pieters *et al.*, (2014), *Am. Mineral.*, 99, 10, [3] Prissel *et al.*, (2014), *EPSL*, 403. [4]Cheek and Pieters, (2014), *Am. Mineral.*, 99, 10. [5]Jackson *et al.*, (2014), *Am. Mineral.*, 99, 10. [6]Williams *et al.*, (2016), *Am. Mineral.*, 101, 3. [7]Li and Milliken, (2016), *JGR*, 121, 10. [8]Donaldson Hanna *et al.*, (2014), *JGR*, 119, 7. [9]Simon S. et al. (2022), this meeting.