PETROLOGY OF THE OLIVINE MOUNTAINS AT COPERNICUS. C. M. Pieters, S.F. Pratt and J.M. Sunshine, Dept. Geological Sciences, Brown Univ., Providence RI 02912

Olivine has been detected as a major component of local rock types at several unsampled sites on the lunar nearside using earth-based near-infrared spectrometers. It is suspected to be abundant in the late Ti-rich basalts of the western mare (1) and is present in deposits from a localized pyroclastic vent in the north polar area (2). Olivine was discovered to be the primary mafic mineral comprising the central peaks of Copernicus (3). It was also found to be a significant component of material excavated along the south rim of Aristarchus as well as a major component of a mountain (massif) on the Aristarchus plateau (4). In all cases, the existence of significant olivine was inferred from the general character of diagnostic absorption features near 1 μm observed in remotely obtained reflectance spectra. To address the more important compositional questions about mineral abundance and mineral composition requires more sophisticated approaches than were previously available. Several techniques for deconvolving mineral mixtures into components and quantifying mineral absorption features have been recently tested and show promise for lunar applications. Presented here is an approach to extract quantified compositional information utilizing the Hapke model for separating components of intimate mixtures (5, 6) and the modified Gaussian model (7) for analyses of mineral composition (8). The discussion below evaluates the composition of the Copernicus mountains.

The central peaks of Copernicus are tens of kilometers in size and represent material excavated from a depth of about 10 km within the crust. The abundance and composition of the olivine is directly related to the origin of this unusual lithology, which in turn bears on the evolution of the lunar crust in this part of the central nearside. A Mg-rich dunite deposit of this size would likely represent a cumulate from a large-scale differentiation event (a pluton or even the mantle formed from a magma ocean). A more Fe-rich olivine deposit would imply extensive intrusion of a rather evolved magma. Although the crater is thought to be about 800 My old (9), the soil at Copernicus is believed to have reached a state of maturity about comparable to typical highland soils, since the optical properties of soil on much of the rim and ejecta is similar to that in the central highlands or at Apollo 16 (10,11).

Regolith Alteration. To extract information about mineral abundances from a composite spectrum requires accurate measurement of the character and the strength of absorption features as well as the overall albedo of the original lithology. Although the soil formation process significantly darkens lunar material and reduces spectral contrast, the residual absorption features retain the characteristics of the original lithology (e.g. 12). The alteration products contained in lunar agglutinates dominate the optical properties. Particle size effects are insignificant due largely to the fact that all soils have a range of particle sizes (13). Shown in Figures 1 and 2 are preliminary results from a two-step approach for removing the effects of alteration from the spectrum for the middle central peak of Copernicus (Cop P3). The first step is to derive a model for the optical properties of the alteration products for typical highland soil. Noritic breccia 67455 was chosen for this preliminary study to represent typical unaltered lithology and soil 62231 was chosen to represent the local mature soil. The intimate mixing model was used to calculate the properties of alteration products required to transform the breccia into mature soil. If particle size and density are comparable, 70% of the synthesized alteration product (ALT) shown in **Figure 1** is required to produce soil 62231. [If the absorbing species in ALT is smaller, the proportion required decreases, but ALT remains the same.] Assuming the same alteration process at Copernicus, the second step is to remove the effects of ALT from the spectrum for Cop P3 using the intimate mixing model (in reverse). In this case, derivation of the unaltered Copernicus P3 spectrum shown in **Figure 2** required removal of 50% ALT from the original telescopic spectrum.

Mineral Abundance. The strength of the broad olivine absorption band near 1 μm in the unaltered Copernicus P3 spectrum is about 40%. Although it can vary with composition, such an absorption strength is typical for particulate monomineralic samples of olivine that contain fine particles (**Figure 3**). A large plagioclase component would be inconsistent with the unaltered Cop P3 spectrum since the plagioclase spectrum (relatively featureless) would dilute the mafic mineral absorption band. In comparison with variations in band strength observed for analogue lunar soil mixtures of plagioclase and pyroxene (13), an upper limit of about 30% plagioclase is estimated for P3. Contrary to previous expectations using simple continuum removal techniques (3, 12), there does appear to be a weak feature in the unaltered Cop P3 spectrum near 2 μm. Two possible causes for this faint absorption are minor components of (1) low-Ca pyroxene or (2) spinel. Pyroxene abundance is simple to estimate and remove with the intimate mixing model. Using the spectrum of a lunar orthopyroxene (separate from 78235), the low-Ca pyroxene component was estimated to be 4-5%. The unaltered Cop P3 spectrum with this minor pyroxene removed is shown in the top of **Figure 2**. Alternatively, trace amounts of spinel could account for the faint 2 μm feature. Only two particulate lunar olivine samples have been available for spectral measurement (72414 and a 76535 separate), both of which exhibited a 2 μm feature and were known to contain noticeable amounts of translucent Cr-spinel. Diffuse transmission measurements on a thinsection of 72415 confirmed the cause of the 2 μm feature to be the spinel in these pristine lunar olivines. Diffuse thinsection spectra and a comparison spectrum from a particulate sample are shown in **Figure 4**. Since the spinel crystals were smaller than the 1 mm beam size, the characteristics of the spinel were calculated from the olivine and the olivine + spinel spectra. In contrast to unmixing pyroxene, however, it is more difficult to confidently remove minor spinel from the Cop P3 spectrum. Reflectance models have not yet been tested that can incorporate these recent thinsection data.

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Mineral Composition. Once the olivine has been separated from the other components (ALT, orthopyroxene, spinel), the complex Fe^{2+} olivine feature can be deconvolved into individual absorption bands using the modified Gaussian model (MGM) (7). If P3 band characteristics are adequately constrained within the S/N of the telescopic data, the composition of the olivine at Copernicus can be estimated by comparing P3 band parameters with the systematic variations observed as a function of composition for the terrestrial Fo - Fa suite (8).

Summary. Although the character of ALT is preliminary, these initial results indicate that the centermost, and blockiest, mountain of Copernicus appears to be composed almost entirely of dunite. Plagioclase is not required, but may be present to <30%. The P3 mountain lithology also contains either 4-5% low-Ca pyroxene or trace amounts of spinel comparable to those found in several pristine olivine samples. When the cause of the 2 µm feature is more fully understood, determination of the olivine composition should be possible. It should be noted, however, that P1, the larger olivine-bearing mountain 10 km to the west (11), must contain an abundant feldspar component since the olivine absorption strength observed for P1 is about 1/3 that at P3 and there are no other significant features in the spectrum (11, 12). The spatial relations of such a distinctive compositional sequence is suggestive of an exposed layered pluton, perhaps similar to that found at the Stillwater complex on Earth.

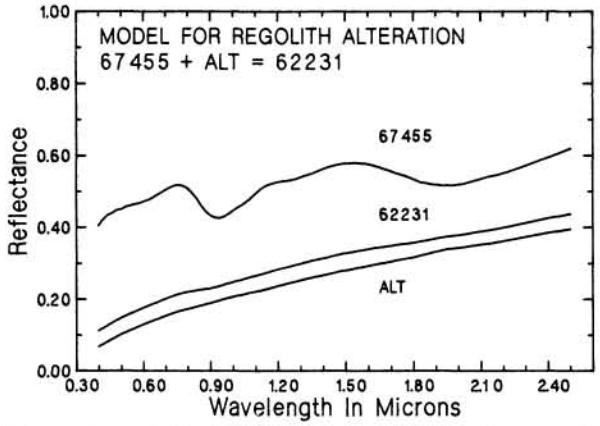

Figure 1. Reflectance spectra of samples used to estimate the required spectral characteristics of materials produced during regolith alteration (ALT). Based on an intimate mixing model, an unweathered breccia (67455) mixed with 70% ALT will produce mature soil (62231).

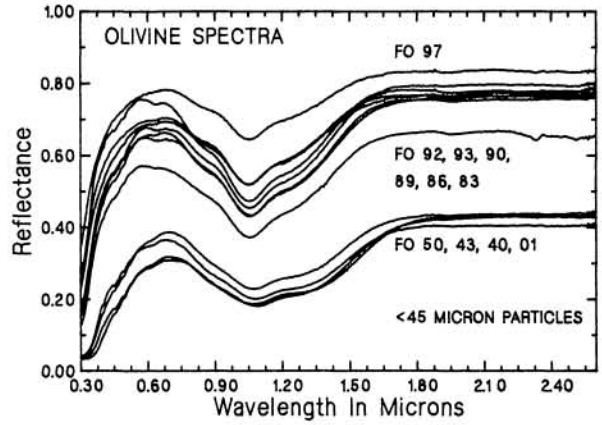

Figure 3. Reflectance spectra of a suite of terrestrial olivines with different compositions [used in Sunshine and Pieters (8)]. All samples have a particle size <45µm.

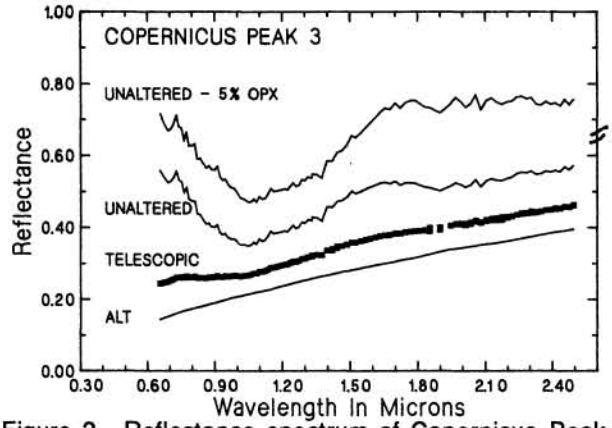

Figure 2. Reflectance spectrum of Copernicus Peak 3 (P3) obtained with earthbased telescopes (with errorbars). Using intimate mixing models, ALT was first removed from Cop P3 to produce a spectrum for unaltered material at P3, then minor (5%) orthopyroxene (78235) was removed resulting in a dunite spectrum (offset upward 0.1).

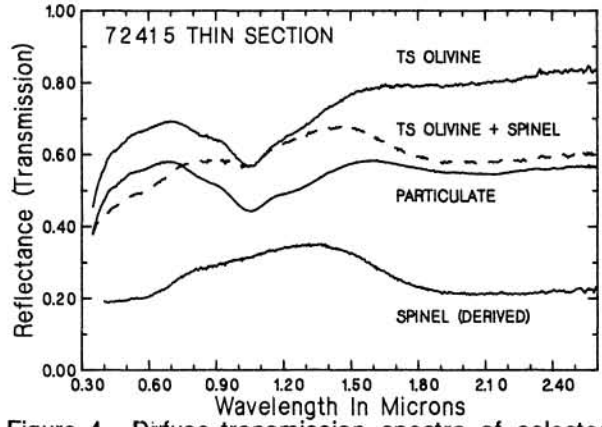

Figure 4. Diffuse transmission spectra of selected areas of olivine and olivine + spinel from a 72415 thin section. The spectral properties of the more absorbing spinel was calculated using linear mixing model. A reflectance spectrum of a particulate sample (<45 µm) of this dunite exhibits a distinct spinel feature near 2 µm.

References: **1.** Pieters C.M. et al. (1980) *JGR*, 85, 3913-3938. **2.** McCord T.B. et al. (1981) *JGR*, 86, 10883-10892. **3.** Pieters (1982) *Science*, 215, 59-61. **4.** Lucey P.G. et al. (1986) *PLPSC16th*, D344-D354. **5** Hapke B. (1981) *JGR 86*, 3039-3054. **6.** Mustard J.F. and Pieters (1986) *LPSC17th*, *JGR 92*, E617-E626. -- (1989) *JGR 94*, 13619-13634. **7.** Sunshine J. et al. (1990) *JGR*, in press. **8.** Sunshine and Pieters (1990) LPS XXI, these volumes. **9.** Eberhardt et al. (1973) *Moon 8*, 104-114. **10.** McCord et al. (1972) *Moon 5*, 52-89. **11.** Pieters et al. (1985) *JGR*, 90, 813-816. **12.** Pieters (1986) *Rev. Geophys Phys. 24*, 557-578. **13.** Crown D.A. and Pieters C.M. (1987) *Icarus 72*, 492-602.