tion of a ray at about six crater radii from Copernicus (frame AS17-2290). Using a conservative excavation depth/diameter of 1/10 and requiring the boundary between the ray and mare substrate to be at least one third the excavation depth, the ray thickness would be of the order of 10–15 m. Thinner rays would allow smaller dark-haloed craters to be produced. These observations imply that the vertical mixing zone of primary ejecta with local substrate that forms the ray could extend throughout most of the regolith where the ray is locally extensive. It also implies that much of the current extent of Copernicus's ray system will remain as a visible feature on the lunar nearside for at least another aeon of lunar history, since this compositionally distinct ray material is apparently an integral part of the regolith.

Data for areas R6 and R7 are more difficult to interpret than those for the proximal areas on the continuous ray because in this case both R6 and R7 possess an immature soil component and have a high radar backscatter, and yet the two areas have very different surface morphologies. Area R6 contains no craters with morphologies that indicate a secondary origin; all the craters are roughly circular and lack the characteristic V structures and braided or mantled texture. Conversely, area R7 contains several well-preserved secondary craters larger than 3 km in diameter and has many smaller, mantled, secondary craters and a prominent set of herringbone dunes.

The most likely explanation for the occurrence of immature soils at both R6 and R7, on the assumption that each area is indeed the age of Copernicus (about 800 million years [*Eberhardt et al.*, 1973]), would be that at both areas an additional physical property has prevented the surface soils from reaching maturity by normal soil formation processes. Steeper local slopes occur within the interiors of the larger secondary craters of R7 than on the exterior deposits (Figure 7) and would cause downslope movement of material during soil-reworking processes, thus preventing normal soil accumulation.

Images of area R6 (Figure 8), however, show an absence of craters larger than a few hundred meters in diameter. Although a different reason for the lack of soil formation may thus be required for R6, the high backscatter of the radar data for both areas puts general constraints on the possible causes. These data show that both area R6 and area R7 are unusually rough (i.e., bright) at the 3.8-cm radar wavelength. Such roughness may be due either to a higher than average number of blocks at the surface (or buried within a few radar wavelengths of the surface) or to local topographic undulations at a scale of a few tens of centimeters [*Zisk et al.*, 1974; *Thompson et al.*, 1981]. Since neither of these physical features are readily observed at R6 within the available image resolution, it is difficult to account for the high radar backscatter and associated immature soil. Most surface boulders should have been removed by maturation processes acting over the history of the ray element [*Arvidson et al.*, 1975]. Unusually rough small-scale topography, unobserved directly, may be more likely to account for the observations, but the direct cause for this roughness is not defined. R6 does lie near the end of a mare ridge system, although no unusual morphology is observed.

4. Quantitative Models

Most of the questions relating to the nature of crater rays require an understanding of how ejecta from the primary crater interacts with local surrounding material. Models derived from the ballistics of ejecta emplacement developed by Oberbeck and coworkers [*Oberbeck*, 1975; *Oberbeck et al.*, 1975] were summarized in the introduction. The compositional measurements for the Copernicus ray described in the previous section are new data directly relevant to the details of this interaction. Since these compositional data are a completely independent source of information about ray materials, it will be useful to compare quantitative results for models of mixing systematics based on ballistic data with recent models of reflectance properties of compositional mixtures. A first-order approximation suggests that there are four types of surface material associated with Copernicus's ray system: mature and immature noritic material derived from the primary crater and mature and immature basaltic material derived from the local mare substrate.

As described in the previous section, the reflectance spectra of the areas on the ray extending out from Copernicus to area R5 increase regularly in slope and in the depth of the pyroxene band. Additionally, the pyroxene band minimum shifts from 0.91 μm toward 1.00 μm, which is consistent with a change from orthopyroxene-bearing anorthosite-norite rocks to clinopyroxene-bearing basalts [*Adams*, 1974]. This change of lithology along the ray is interpreted as an expression of the mixing of differing proportions of Copernicus ejecta with the mare basalt substrate. The kind of mixing and the relative proportions of the rock/soil types warrant further examination as a means of better understanding the process of ray emplacement.

Two models are used here to describe the spectral reflectance changes that occur when different materials are mixed. One model applies where patches of one material are interspersed with patches of another so that any small packet of reflected radiation has interacted with one material only. This is the so-called "checkerboard" or linear model where the spectral reflectance contribution from each material is weighted linearly by the areal extent of the material [*Singer and McCord*, 1979]. For the lunar rocks/soils being considered, the scale of mixing may range from centimeters to kilometers or larger and cannot be specified using the reflectance data.

The second model describes reflectance from mixed materials when small packets of radiation have passed through each material present. The model applies to lunar soils which contain rock, mineral, and glass particles typically on the scales of millimeters to microns in diameter. The spectral reflectance contributions of the individual soil components do not add in a linear fashion but instead are weighted by such factors as the optical extinction coefficients of the particles. The nonlinear mixing of intimate mixture of minerals in soil spectra is described by *Johnson et al.* [1983] and involves the calculation of single-scattering albedos from individual components. The method is also sensitive to particle-size effects on reflectance spectra.

The telescopic reflectance data for all areas associated with Copernicus's ray were examined with both mixing models. Many areas along the ray were measured more than once. We have included some of these multiple measurements to indicate the range of data variations due to observational parameters. Principal component analyses (PCA) were used to describe the systematic variations of the reflectance data in terms of mixing lines between a variety of compositional end-members. Separate PCA analyses were made to test the linear checkerboard and the nonlinear intimate mix models.

Procedures

The telescopic reflectance spectra for the Copernicus ray areas were filtered using a five-point running mean to suppress random instrumental errors. Thirty wavelengths between 0.7